STATE-OF-THE-ART FIBER OPTICS AND ITS APPLICATIONS TO THE SHIPBOARD DATA MULTIPLEX SYSTEM

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AND ITS APPLICATIONS TO THE
SHIPBOARD DATA MULTIPLEX SYSTEM

by

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This thesis contains an overview of the present status and possible future roles of fiber optics for shipboard applications. Subjects addressed include state-of-the-art materials and fibers, their optical and mechanical properties, environmental testing, design of fibers and cables and fiber systems. Specific shipboard applications of fiber optic systems are related to the Navy's Shipboard Data

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by

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ABSTRACT

This thesis contains an overview of the present status and possible future roles of fiber optics for shipboard applications. Subjects addressed include state-of-the-art materials and fibers, their optical and mechanical properties, environmental testing, design of fibers and cables and fiber systems. Specific shipboard applications of fiber optic systems are related to the Navy's Shipboard Data Multiplex System (SDMS) along with the advantages and payoffs expected with deployment. The fiber optics market is discussed including an economic analysis of fiber optic technology versus conventional coaxial cable. Present major advantages and problem areas confronting decision makers when considering fiber optic systems are outlined. Conclusions and recommendations suggest that the rate at which the evolution of fiber optic applications progresses is primarily a function of the aggressiveness at the system management level and the timely solution of technical deficiencies.

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I. INTRODUCTION

A. GENERAL

The operation of a fiber waveguide is governed by the simple laws of geometrical optics and electromagnetic theory. Light injected into a fiber at the proper angle will undergo internal reflection at the walls and will propagate along the length of the fiber until attenuated by absorption and scattering mechanisms. By cladding the central core material of the fiber with a lower-index material to achieve a protected, reflective interface, and through the use of homogeneous, ultra high-purity glasses, attenuations of less than 1 dB/km [1] have been achieved in optical fibers, far lower than conventional coaxial cables. A basic fiber communication link consists of a modulated light source such as GaAs light-emitting diode (LED) or a laser diode, the fiber waveguide, repeaters to periodically amplify the signal, and a photodetector such as silicon PIN or avalanche diode. Operation is normally confined to the near-infrared region ($.8\mu < \lambda < 11\mu$), which corresponds to the maximum transmission region of the fiber waveguide.

For example, GTE [2] has instituted regular telephone service on optical fiber links for General Telephone customers in Artesia, California. The system connects the long-distance switching center at Long Beach with the local exchange building in Artesia, 5.6 miles away. The link handles

long-distance calls to and from Artesia, with one fiber each for incoming and outgoing signals. The analog voice signals are converted to binary digits and assigned individual time slots for transmission. These electrical pulses are converted into near-infrared light signals by a light-emitting diode and are then pulsed along the optical fiber. The light source for the system is an LED approximately the size of a salt grain. These diodes are multi-layer gallium-alluminum-arsenide heterostructures emitting signals at 815 nanometers with an average power of about 60 microwatts. The average lifetime is approximately 3000 hours.

At 1.6 miles from the Long Beach station the signal enters a repeater which strengthens and retransmits it another 2.3 miles. Entering another repeater, the signals are transmitted to the Artesia switching center which is an additional 1.7 miles away. The repeaters utilize avalanche photodiodes and LED's to boost the signal and repair any distortion occurring in transit. If the regenerative circuits in the repeater detect a pulse, a new, noise free, undistorted pulse is sent to the LED, which transmits the information at a rate of 1.544 M bits. Other such telecommunication capabilities have been demonstrated by the Bell System in Chicago and the Japanese High-Ovis Project in Osaka, Japan [3].

B. HISTORICAL BACKGROUND OF OPTICAL SYSTEMS IN THE NAVY

As of November 1977 the Naval Underwater Systems Center (NUSC), Naval Air Development Center (NADC), and Naval Electronics Lab Center (NELC) (now the Naval Ocean Systems Center (NOSC)) have been concerned with communication to submarines, where the optical communications link does have a significant advantage, i.e., it alone of all electromagnetic radiation (except ELF) can penetrate the water in the blue-green region. Therefore, the submarine need not surface to receive information and expose itself to detection. This single advantage is sufficient for the Navy to have spent significant funds on in-house development, and to include fiber optic communications in their future telecommunications architecture.

The naval systems being considered for fiber optic applications can be divided into four categories: airborne, undersea, shipboard and land-based platforms.

In airborne applications such as the A-7 airborne light optical fiber technology (ALOFT) [1] program, the system requirements are such that fiber optic techniques could have an immediate impact (short distances, good environmental conditions, light-weight requirements, good opportunity to use multiplexing, etc.) and, in fact, off-the-shelf components could probably be used. Not only are cable-to-cable and cable-to-device couplers required, but also devices for connecting an optical fiber to a number of spatially distributed

terminals. Since this requires power combiners, dividers, multi-terminal taps and star couplers, technology in this area needs definite improvement.

Undersea applications involve towed arrays, sonobuoys, torpedo guidance, and tethers or umbilicals for various searching and mapping missions. The demands for these applications primarily affect the fiber cable itself and are largely concerned with its physical characteristics (i.e., effects of salt water, tensile stress, ability to withstand reel stresses, etc.).

Shipboard fiber optic applications are in a way similar to aircraft applications, particularly when considering smaller craft such as hydrofoils and air cushion craft. For larger vessels, the increase in distance adds a further dimension to system performance requirements. The Navy has already implemented a six station fiber optic telephone system on the USS Little Rock (to be discussed later in the text) and a video fiber optic link aboard the carrier USS Kitty Hawk.

Land-based platform applications for fiber optics are much the same as for the other branches of the military. The Navy is conducting programs to establish a fiber optic link between the antenna and transceiver of a Marine Corps tactical radar as well as other land-base data transmission links.

II. SYSTEM COMPONENTS

A. OPTICAL FIBER CABLES

1. General

A simple fiber optic cable is shown in Figure 1 [4]. It has a circular core of diameter d and uniform refractive index n_1 surrounded by a cladding layer of refractive index, n_2. Light launched at angles within θ_1 will be propagated within the core at angles similar to θ_2. Light launched at angles greater than θ_1 will not be reflected internally but refracted into the cladding or even out of the cladding into the air. The maximum launch and propagation angles are related mathematically to the numerical aperture, NA (a number that expresses the light-gathering power of an optical-fiber cable):

$$NA = (n_1^2 - n_2^2)^{1/2} = \sin\theta_1 = n_1 \sin\theta_2$$

As in any electromagnetic waveguide propagation, only certain modes can propagate in fiber optic cables. The number of modes, M, is related to the light wavelength, λ, in the following manner:

$$M = 0.5 \left(\frac{\pi d NA}{\lambda}\right)^2$$

where d = core diameter. Thus, for any NA or refractive indexes and light wavelength λ, M will always decrease as

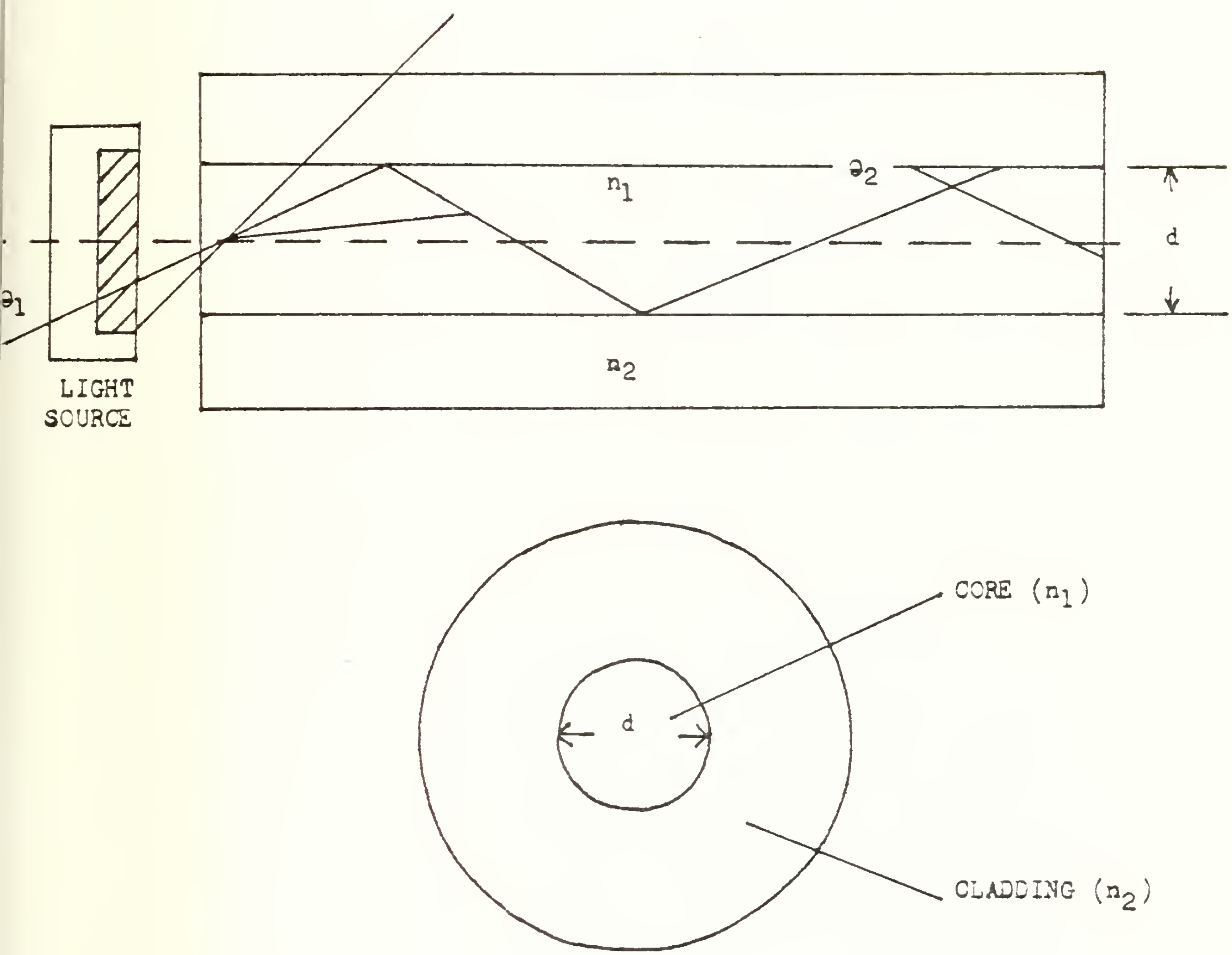


Fig. I. STRUCTURE OF A TYPICAL MULTIMODE STEP INDEX CABLE. After Reference [4].

the diameter of the core is reduced. Only a single mode will propagate when the core diameter approaches the light wavelength.

First of the three most commonly used fibers is the single-mode fiber. Its core is very small, i.e., on the order of the light wavelength λ. For this reason, the small diameter of the core causes an inefficient coupling between the light source and the cable because only that portion of the light rays which strike the fiber at angles less than θ_1 in Figure 1 would propagate. An advantage however, of the single-mode, fibrous cable is that no mode dispersion is introduced in the propagation.

Second is a multimode, step-index fiber (the core and cladding have an abrupt change of refractive index) and allow for more efficient coupling by the use of a larger core. However, a penalty for the improved coupling is the mode dispersion caused by the larger path differences between the extreme modes.

Thidly is the graded-index, multimode fiber with a refractive-index profile that gets progressively lower away from the axis. This profile tends to give the same delays to different modes, and thus, lowers the dispersion effect.

2. Mode and Material Dispersion Effects

In addition to the mode dispersion just described, there is another dispersion-effect called material dispersion, which is due to the difference in the propagational velocity

of light of different wavelengths from the light sources. Practical light sources are not monochromatic (one color); the spread in wavelength may be as much as 50 nm from a LED and 4 nm from a laser.

The mode and material dispersion effects are the principle factors determining the bandwidth or bit-rate capacity of a fiber optic system.

Both of these effects cause a light pulse injected in one end of a fiber to broaden as it propagates down the wave guide. In the mode dispersion case, axial modes travelling the shortest distance along the fiber will arrive before those repeatedly reflected off the walls of the waveguide. Material dispersion results since the velocity of light in an optical material is frequency dependent. Therefore light from broad-banded light sources such as LED's spreads out as it travels along the fiber. Material dispersion can be minimized by the use of narrow spectral sources such as laser diodes. Modal dispersion can be sharply reduced by the grading of the fiber index over its cross section, which equalizes the effective optical path traversed by all rays regardless of mode. Most present day fibers for long distance, high-data-rate applications are of the graded index type.

3. Attenuation

Another important characteristic of an optical fiber is its attenuation or transmission loss. Attenuation is due

to absorption (the conversion of light into heat) caused by the fundamental fluctuations in glass density, composition, and discrete imperfections. Absorption loss can be reduced by controlling the impurities of the core material and scattering loss reduced by careful fabrication of the core. It was found that scattering loss is inversely proportional to the fourth power of the light wavelength. Present fiber optic systems are operating in the vicinity of 0.8-1.0 μm which is not optimum when considering attenuation. Intensive effort is being exerted to develop the components, particularly the optical source and detector, at longer wavelengths to reduce attenuation.

4. Parameters for Fiber Optic Cable Selection

The following are important considerations when selecting fiber optic cables:

Length - The most important consideration in choosing fiber optic cable is the length of the system. Length can limit the transmission of both power and bandwidth, and the proper choice of cable can optimize this transmission.

Data-rate - In short-length cables, data rate limitations seldom occur. But in long-length cables, data rate can be a problem since cable bandwidth decreases linearly up to some equilibrium length, typically 1/2 kilometer. Beyond that, the bandwidth appears to decrease as the square root of the length. Therefore, by determining whether either low numerical aperture or graded-index cables are required, one can optimize the system data transmission.

Source Wavelength - Attenuation of most fibers tends to be at a minimum at certain wavelengths such as .82 μm and 1.06 μm [5]. However, the range between .82 μm and 1.06 μm, for example, at .9 μm where reliable GaAs sources exist, has high attenuation factors due to water absorption bands.

Number of Channels - Each signal channel should have its own fiber on which to transmit since two-way transmission on a single fiber requires additional coupling losses on input and output. Therefore, whether the number of channels are provided all in one cable or in several cables on a modular basis is up to the discretion of the user when considering his cost, space and weight requirements.

Budget - There may be several fiber optic cables that would be suitable for a given system. However, for more money, greater improvements may be built into the system. For example, if a very high bandwidth graded-index cable were used rather than a moderate bandwidth, low numerical aperture step-index cable, it could be upgraded in bandwidth as modulation rates and quality of the optical sources increase.

Strength - Fiber optic cables can be made to meet desired tensile or crush strength - the trade-offs appear in size and cost. Making a medium duty cable adequate for heavy duty work may double the cost of the cable, as well as double its diameter. A heavy duty cable should be capable of several hundred pounds tensile strength, enough to pull

through long lengths of conduit. Medium duty cables are strong enough to pull through intra-building cable trays, and light duty cables are useful for laboratory use of system wiring.

Strength-to-weight ratios of fiber optic cables can be much greater than most metal cables, which makes them easier to install. The crush tolerance of many fiber optic cables is also greater than that of conventional metal cables.

B. OPTICAL FIBERS

Optic waveguides may be grouped into four general classes: 1) low loss, low numerical aperture synthetic silica and doped-silica fibers with either step or graded index; 2) moderate-to-high loss complex silicate glasses of moderate to high NA with step or graded index; 3) high loss, high to moderate NA, step-index plastic fibers; and 4) low to moderate loss, moderate NA, polymer-clad fused silica step-index fibers.

These fibers are prepared by chemical vapor deposition (CVD) processes which are responsible for their ultra-high purity, homogeneity and low optical losses. Bell Labs have reorted losses of 0.9 dB/km and Japanese workers 0.5 dB/km in these types of fibers [1]. The three principal manufacturers of low loss fibers in the U.S. are Corning, ITT and Bell Labs. Mode dispersions of less than 0.5 nsec/km have been achieved by both Bell and Corning. Silica fibers are the most attractive for long distance, high data rate

applications and have received the greatest attention in the optical fiber R&D efforts throughout the world. Fujihura of Japan, ITT and Bell Labs have reported strengths as high as 900,000 psi for short lengths of silica fibers.

Corning presently offers a range of 10 graded and step index types of low loss fibers with numerical aperatures of 0.16 - 0.20, maximum losses of 3 dB/km at 820 nm wavelength and bandwidths as high as 1 GHz at 1 km lengths. Environmental testing of these fibers has included exposure to 90% humidity, immersion in distilled, stagnant and salt water, temperatures between -50°C to 70°C, proof testing to 25,000 psi in km lengths and exposure to isostatic pressures up to 20,000 psi. All of the above tests failed to produce any significant degradation in the fibers [1].

The preparation of graded index, low loss fibers by CVD techniques requires sophisticated experimental techniques and analytical facilities that make it difficult for small companies or labs to compete or mount a state-of-the-art program. However several small companies, Amersil (producing Suprasil) and Thermal American Fused Quartz (producing Spectrosil) have produced synthetic silica rods of high purity which have optical losses as low as a few dB/km. By use of a torch, laser, or high temperature furnace, these rods can be drawn into high quality, low loss fibers. The fibers can be immediately dip-coated in a plastic or silicone solution and receive an in-line extrusion of a thick protective polymer jacket. Depending on the silica core

material used, losses as low as 10 dB/km have been achieved through the use of special low-loss silicone claddings manufactured by Shinetsn of Japan.

This new type of fiber is durable, quite strong and lower in cost than the CVD fibers. Therefore, it is attractive for a wide range of military applications including avionic systems, medium distance land lines at tactical command posts, shipboard data transmission and torpedo guidance cables.

Practically all of the early glass fiber optic bundles available since the mid 1960's have been fabricated using lead silicate glass cores and borosilicate or soda-lime silicate glass cladding; the lead being added to produce a high index of refraction. The high indices of lead glasses give these fibers a high numerical aperture, permitting the use of very thin cladding layers since the internal reflection process is very efficient. Although the optical losses of these fibers tend to be high due to the use of commercial grade materials (300 to 1000 dB/km loss), coupling is extremely efficient to both conventional light sources such as LED's and to T-couplers used in multi-terminal networks. In short run applications, such as in the A-7 which had insignificant cable losses, lead silicate fibers were chosen because of their attractive coupling features. However, one severe limitation of lead silicate fibers is their extreme sensitivity to ionizing radiation.

Normally, plastic fibers are fabricated from polymethylmethacrylate (PMMA) and polystyrene. Several companies have marketed high loss fibers for many years in automobiles and medical fiber scopes. Losses are presently high in plastic fibers but it is predicted that attentuations will be reduced to the 200 dB/km level at certain selected wavelengths in the near future. The current losses in plastic fibers do not arise from high intrinsic absorption, but from very high scattering losses due both to unwanted suspended particles and high interface losses. Plastic fibers offer excellent mechanical properties near room temperatures and do not suffer the brittle fracture problems of the glasses. However, there has been no funding of plastic fiber optic materials by the Navy to date. The significant radiation resistance, light-weight, mechanical flexibility and breakage resistance of plastics makes them attractive for many short run applications. Further development with lower optical losses and better thermal stability would greatly extend their usefulness in Navy systems.

For lengths less than 30 meters, high-loss (greater than 100 dB/km) fiber cables are the most practical. In short, they are very efficient at coupling in light because of their large bundle diameters and high numerical apertures. Attenuation per unit length is not very important over short lengths but input coupling is. Therefore, in short lengths, say 20 meters, an inexpensive LED can transmit far more power across a high-loss cable than a low-loss cable.

In the case of a medium loss cable (20-100 dB/km), the numerical aperture unfortunately decreases and thus, the input coupling becomes more difficult. As a result, the distances of medium-loss cables are restricted to 30-500 meters. However, as the numerical aperture decreases, the information carrying capacity increases. Medium loss cables are typically provided in bundles of small fibers, or as oversized single-fiber channels.

Low-loss cables (less than 20 dB/km) are all based on refractive index profiles and are the most promising from a telecommunications standpoint because they efficiently transmit high volumes of data over long distances.

C. FIBER CABLE MATERIALS

1. General

The preparation of high quality fiber optic cables requires a wide range of materials with specific mechanical, optical, electrical and chemical properties. These can be divided into the following functional classes: 1) core and cladding optical materials for transmission of the light signal; 2) fiber coatings to protect and buffer the interior from hostile environments and rough handling; 3) strength-bearing materials of high modulus both to minimize tensile stresses applied to optical fibers and to provide crush resistance; 4) cable filler materials to provide further cushioning and prevention of cable collapse; and 5) protective jacketing which possesses abrasion resistance, chemical

resistance, high impermeability to water, flexibility and any other properties which might be required.

Fiber waveguides presently are fabricated from either silicate glasses, polymers or combinations of both. The specific materials chosen are dictated by the systems optical requirements such as attenuation, numerical aperture, dispersion, coupling efficiency and operational wavelength. As discussed earlier, low loss materials are normally prepared by chemical vapor deposition (CVD) of gases to produce low loss fused silicas and doped silicas. Moderate loss materials are typically less pure silicas and crucible melted, high purity silicate glasses. High loss materials consist primarily of commercial lead silicate glasses and various types of plastic.

Many types of coatings and buffers have been utilized for optical fibers. In-line dip coating and extrusion of protective layers onto freshly drawn fibers is essential if high strengths and low optical losses are to be maintained. In considering a coating, one must include good abrasion resistance, impermeability to moisture, reduction of cross talk, chemical inertness, flexibility, low modulus, and compatibility with cable manufacturing. Usually more than one protective layer is used. A thin, dip-coated layer of a few microns is applied immediately as the fiber emerges from the furnace or torch, and this is in turn overcoated with a thicker, more rigid extruded plastic jacket.

In theory, most fiber optic glasses should possess high intrinsic tensile strengths in the neighborhood of 3×10^6 psi [1]. However, this is rarely approached in practical applications. Some fiber strengths in short gauge lengths presently exceed 10^6 psi in the best fibers. However, as fiber lengths increase to the kilometer range, strengths fall to the range of 10^5 psi or lower since the probability of finding a weak flaw increases with increasing length. Failure almost initiates at a surface defect. More serious is the further fatigue which can take place in initial fiber strengths, when both applied stress and moisture are present. It is essential to provide strength members in most fiber cables to minimize the loading that the optical fibers receive. Strengthening material should have high tensile strength and must exhibit very little elongation under stress (Young's modulus). Strength members are normally employed in the form of multi-filament yarns to achieve flexibility, rather than as solid rods or heavy gauge wires. The most common materials used to date have been Kevlar 49 (low strain), Kevlar 29 (high tensile stress) and steel (low strain, high tensile stress). Other possibilities include glass fibers, boron fibers, sapphire fibers and graphite fibers.

Cable filling materials have been introduced to provide a variety of requirements including: 1) additional buffering to minimize lateral deformation of the fibers which can produce breakage or additional optical losses; 2) prevention of cable kinking under bending and torsion stresses;

3) provision for fiber slippage within the cable during bending to prevent high local tensile stresses; 4) prevention of cable collapse under high hydrostatic pressures incurred during undersea applications; 5) provisions for further optical isolation of neighboring fibers for very low cross-talk requirements; and 6) prevention of moisture buildup in the vicinity of the optical fibers. Present fillers include epoxies, paper tapes, glass yarns, cotton, plastic sheaths and spacers, polyester and teflon tapes, metal tubes, kevlar yarn and polyethylene greases.

Sheathing must possess flexibility, crush and impact resistance, temperature stability, low friction, chemical inertness and water impermeability. In general, sheathing and jacketing materials for both fiber bundles and cables have been assorted plastics and polymers. Some examples are polyvinyl chloride (PVC), polyethylene, teflon, nylon, hytrel and polyurethanes. A tradeoff between rigidity, to minimize stress induced optical losses, and flexibility, to permit winding and coiling, is normally required.

Current Navy programs are directed toward the development of moderate loss (100 dB/km), high numerical aperture, radiation-resistant glasses for fiber optic applications. However, various polymer coatings are also being studied in addition to other materials work being performed on a contract basis by private industry.

D. LIGHT SOURCES

1. General

The best light source for fibers is small, bright, monochromatic, fast and reliable. High radiance assures that plenty of light gets coupled into the fiber. In addition, it must be able to be modulated fast to transmit high bandwidth data. A narrow spectral line width keeps the dispersion in the fiber low. And, naturally, a light source must have a lifetime of thousands of hours.

Laser diodes and LED's are now being developed with factory assembled fiber pigtails attached, which will avoid the need for field alignment of fiber optic devices smaller than a grain of salt. Then, only a simple fiber-to-fiber splice will be necessary.

2. Light Emitting Diodes (LED's) and Injection Laser Diodes

The most commonly used light sources at present are the GaAs LED's (gallium-arsenide light-emitting diodes) and injection lasers. Both are simple and inexpensive devices with sizes compatible to the fiber-core dimensions and with light wavelengths in the range of 0.8-0.9 μm where fibers have low loss and dispersion.

LED's are non-coherent sources which have roughly light-power-versus-driving-electrical current characteristics to the point of saturation of the light output due to device heating [4]. They require peak driving currents of about 100-300 mA and can be modulated directly by varying the

drive current. With a drive current of 100 mA at 2V, about 50 μW of light power can be coupled into a multi-mode fiber. Thus, the overall conversion-efficiency (between electrical drive power and light power captured by the fiber) is about 0.025 percent. LED's have typical optical bandwidth of 40-50 nm or less at room temperature, which results in material dispersion of 3-5 nanoseconds per kilometer. This would give a theoretical bit-rate capacity of several hundred mega-bits per second. However, 50 M bps is probably a more accurate number in practice.

The laser, a semi-coherent source, is a threshold device which begins to operate at a drive current of approximately 100 mA and reaches maximum output levels (limited by mirror damage) with 20-30 mA more current. It can couple a few mW of light power into a fiber and, thus, is about 10-50 times more efficient in conversion. Linearity in the light-power-versus-driving-electrical current is not good, even at an operating point above threshold. Therefore, lasers are considered more appropriate for digital applications. Since their optical bandwidth is much less than that of LED's (2 nm vs 20 nm), material dispersion is not a problem. Thus, they can be modulated by a driving current at gigabit rates.

Lifetime and driver complexity are the more serious disadvantages of the laser with respect to the LED. Although laser lifetime of one million hours at room temperature has been reported by the fiber optic industry, its variation

with temperature (lifetime drops as temperature increases) and among individual lasers is still of concern to systematic designers. The laser threshold also varies with temperature and age, which requires a more complicated feedback-controlled driver to keep the laser biased near threshold.

Both solid state LED's and laser diodes are attractive sources for optical fiber transmission because their output can be rapidly controlled by varying their bias current. Furthermore, their high brightness, small size, emission wavelength, and low drive voltage are also attractive features. ITT, for example, uses LED's and lasers which have a peak emission wavelength in the near infrared at 840 nanometers (nm) [6]. At this wavelength, low and medium loss fibers manufactured by ITT and others exhibit low attenuation and silicon detectors exhibit high responsivity. Lasers can produce 10 dB or more optical power output than LED's. Since the source light output must be coupled into the fiber for transmission, coupling losses must be taken in account in evaluating sources. Coupling loss depends on fiber acceptance characteristics and source emission characteristics. Due to greater power output and a narrower emission angle, lasers couple, typically, 10 dB more power into a fiber than do LED's.

While the laser offers high power output, high coupling efficiency, and high conversion efficiency, it must be operated in a restricted current range just above its lasing threshold current. Since the threshold current

may change with time and temperature, practical laser drive circuits must incorporate compensation for these effects. When their bandwidth and coupled power is adequate, LED's are attractive for use instead of lasers because of lower cost, longer expected lifetime, wider temperature range, and greater long-term stability.

For either optical source, the driver must supply the required current to the low dynamic inpedance of the diode at the desired modulation rate. The peak and average current must not exceed that recommended for the diode and in the case of lasers, the peak power output must not exceed the recommended value.

The drive circuit is designed to accept an input signal and convert it to a current drive for a specific diode light source. In the case of digital signal transmission, the driver usually consists of a high speed pulser, which switches the diode on and off. In some cases, the driver is designed to supply additional turn-on and turn-off current spikes to overcome the effect of diode capacitance and thus shorten optical rise and fall times. In the case of laser diode sources, the driver may be designed to supply an additional pre-bias current at just below the laser threshold level. The diode can then be switched more rapidly into the lasing mode. Drive current compensation may be necessary for the laser diodes, as threshold current is temperature dependent. An auxiliary optical detector may

be incorporated in the laser drive circuit to compensate for possible threshold drift and also to prevent excessive optical output power.

In baseband analog signal transmission, the driver must supply a quiescent drive current to the diode to give an output of about half of peak to allow transmission of both positive and negative signals. In order to overcome the non-linear voltage-current characteristic of the diode, the driver should act as a pure current source controlled by the input voltage. For most LED's, the current-to-optical power characteristic if fairly linear; however, in order to achieve intermodulation levels below about -30 to -40 dB, optical signal feedback from an auxiliary detector may be required.

3. Performance Characteristics [7]

The function of a light source (transmitter) is to convert an electrical waveform into an optical waveform for introduction onto an optical fiber. The important performance characteristics for a light source are:

a. output power.

b. compatability with the fiber.

c. modulation bandwidth.

d. stability.

e. lifetime.

f. cost.

Two structures currently offering the most promise are the surface emitting LED (Burrus) and the edge-emitting LED. Of these, the edge emitting diode is capable of coupling more power into a fiber optic cable.

E. COUPLERS

1. General

Couplers are used to optically interconnect fiber optic components. Depending on the application, the system designer chooses either a permanent optical connection (a splice) or a connector which may be disconnected and reconnected many times (a connector).

Couplers may be used to interconnect single elements, for example, one cable to one cable, or can be part of a distribution system wherein optical signals are sent to or received from a set of remote terminals.

Due to the fact that most light emitters and detectors are now manufactured with a short length of suitable optical fiber permanently attached, the coupling problem usually develops when two fiber optic cables (single fiber or bundles) are interconnected.

In making a splice or termination with bundles, moderately careful alignment is required. The fibers are held together as a unit with epoxy, and are then ground and polished to a smooth optical end finish.

Because of the very small active core area in single fibers, and the very small emitting area of single-fiber

sources, alignment is very critical. For efficient coupling of single fibers, the separation axial and lateral alignment tolerances must be on the order of a few microns.

Optical loss is present in a connector or splice due to the discontinuity produced at the junction. Siecor has demonstrated a typical insertion loss for splicing at 0.5 dB and a 0.4-0.7 dB loss for in-line connectors [8]. ITT quotes average losses of 1.0 dB for connectors and 0.3 dB for splicing [6]. On the other hand, with respect to coupling efficiency, Valtec lists "good" for both edge emitter and Burrus LED's and "excellent" for injection laser diodes [9].

Currently there are three main types of couplers (power combiners and dividers) being used for the distribution of wide-band optical signals (primarily digital data) to a set of remote terminals. They are the Tee, star and bi-fircated (two-forked) couplers [10].

The star coupler consists of a glass mixing rod with a silver-mirrored surface on one end and several fiber bundles attached permanently to the opposite face of the mixing rod. Light signals are transmitted via one fiber bundle to the mixer-coupler where the light rays are reflected back to other bundles. Insertion loss is approximately 1 dB per receiver bundle.

Tee couplers are formed by bonding bent Pyrex arms to a mixing block. Unidirectional couplers have been formed in this manner exhibiting approximately 1.5 dB insertion loss, exclusive of the tap loss.

The third type of access coupler uses bifurcated (and trifurcated) fiber bundles that are also commercially available. These have exhibited insertion losses of 1.5 dB.

2. Connectors and Connecting Techniques

Connectors are actually couplers which can be connected and disconnected many times with negligible change of characteristics. Generally, most connectors exhibit an insertion loss of approximately 2-3 dB, which tends to increase with environmental changes (moisture, dirt, dust, etc.) and with use. However, four connector fabrication techniques are under investigation.

The first is a plug-in coupler wherein the fiber end is cemented inside a capillary tube which is then bonded to the connector shell. Under "ideal" conditions, this technique proves to be very effective inasmuch as it has low losses ($\approx$ 1.0 dB) and good connect/disconnect reliability. However, the critical angular and lateral alignments necessitate precision fiber-locator tools needed to center and align the fiber with respect to the connector shell. Heat-cured epoxies are also used, which require control of curing time and temperature. Finally, the fiber end must be polished to achieve low connector loss.

A second connector technique, using three deformable precision rods within a precision cylinder, has the advantage of compensating for fiber cladding variations due to the manufacturing process. However, the use of three rods within

each connector piece (jack and plug), presents the great disadvantage of mechanically aligning the fibers at the jack-plug interface. Problems with angular and lateral alignment as well as separation of fiber ends may occur at this interface due to the mechanical alignment. Axial alignment is usually the largest of the three problems because of the difficulty in maintaining fiber end separation at less than a few microns as required for low loss connections. End-loading to minimize the separation between fiber ends cannot be used due to the distortion of the deformable rods which would occur from the force necessary for proper fiber end-loading.

The third technique is that of the V-groove design, in which a small precision V-groove is used for the fiber alignment within the connector jack. By using this technique, fiber alignment is accomplished within the one V-groove provided by the jack, thus eliminating the critical mechanical jack-plug interface alignment problem associated with the three rod technique. The covered V-groove creates a precision triangle, which centers the fiber core. Using a deformable material for the V-groove and its cover, fiber cladding tolerances are absorbed and good lateral and angular alignment is achieved. In this method, end-loading can be used providing low fiber end separation losses without the use of index-matching oils. A critical part of the connector design using this principle is the material selection for the V-groove and its cover. The surface must

be soft enough to allow the necessary deformation to accommodate a range of fiber diameters, but not so soft as to be easily marred or subject to cold flow. By proper material selections, problems of fiber connections using the V-groove technique are minimized.

The fourth technique employs an eccentric coupler, in which the axis of the fiber within the plug is offset with respect to the plug axis of the outer shell. Two such eccentric plugs are then mated together in a V-groove for the connection. The light transfer through the connector is tuned by rotating the plugs within the V-groove. This tuning ability of the eccentric coupler is its greatest advantage; once properly tuned for maximum light transfer, the connection exhibits very low loss. An alternative configuration to the double plug eccentric coupler is a bulkhead-mounted jack having a stationary fiber mated with a double eccentric plug. The tuning in this design is accomplished by rotating only the plug. Disadvantages of the eccentric coupler are the need for tuning the connection and polishing the fiber ends.

3. Splices and Splicing Techniques

Cable splicing is used for permanent connection between single fibers or fiber bundles and techniques for splicing cables have been much better established than cable connector techniques.

Presently, three fiber splicing techniques are in use in the industry: 1) the electric arc welding system;

2) the British Post Office system; and 3) the epoxied V-groove system.

Electric arc welding systems involve the actual welding of the fiber ends, using precision welding and fiber alignment equipment. Typically, the arc welder is precisely controlled using XYZ positioners and servos, and the fiber ends are aligned and securely held by a precision vacuum clamp. High quality splices have been achieved in laboratories, but the use of such elaborate equipment in the field is highly impractical.

The British Post Office system is a much simpler splicing technique. Fundamentally, a special fiber aligning jig is used to bring the fiber ends together in a base in which there is a very thin V-groove platelet. A laser is coupled into one of the two fibers to be spliced, while the base is adjusted. The base is properly adjusted when no scattered laser light is observed at the fiber splice. Index-matching epoxy is then applied to the fibers in the platelet. After heating and curing the epoxy, the fibers with the now-attached platelet are removed from the base. Essentially, no stress is applied to the fibers by the platelet due to its negligible weight. Plastic strength members and heat-shrink tubing are used to join the fibers' outer jackets together. The completed splice assembly provides a strong, low-loss fiber cable connection. Once again however, the necessary heating for epoxy curing makes the British Post Office system impractical for field use.

The third technique, developed by Siemens AG, uses V-shaped grooves for centering the fibers to be joined after breaking them normal to their axis. A drop of transparent adhesive holds the fiber ends in position and acts as an immersion substance at the same time.

The V-groove consists of a low cost piece of bent sheet metal material. This V-groove is raised toward the two fibers held in an oblique position. The sides of the groove catch the fiber ends and center them automatically. Furthermore, this upward movement of the groove presses the fiber ends together slightly and axially aligns the fibers. The fibers are fixed now with the quick-setting, transparent adhesive. According to the results of a field test by Siemens AG (using 2.1 km of 10-fiber cable with 60 splices), splices made under field conditions show losses not significantly different from the lab findings [7]. Therefore, it may be safe to say that 0.5 dB loss per splice will occur when calculating link loss power budgets.

F. DETECTORS

1. General

Optical detectors are well developed. The most ideally suitable for operating systems in the 0.8-0.9 μm wavelength region are two main silicon types, the PIN photodiode and the avalanche photodiode (APD). These detectors convert light power input to electrical current output, with excellent quantum-efficiency (the ratio of primary

photo-electrons generated to photons incident on the detector) in the order of 90 percent, fast response time in the order of 1 microsecond, and low noise in the order of -54 dBm [4].

2. PIN Photodiodes

PIN diodes are simple devices, easy to use, but their sensitivity is not high. Sensitivity is the minimally required input-light power needed to achieve a given performance level signal-to-noise ratio for analog systems and error rate for digital systems. Thus, their performance is limited by the thermal noise in subsequent amplifiers after detection.

3. Avalanche Photodiodes

APD's give better sensitivity because the avalanche process provides large amplification, as much as 100 times within the detector, thus, provides a large output current and reduces the effect of subsequent after-detection amplifier noise. However, the avalanche process also generates noise within the detector. The overall improvement in signal-to-noise ratio of an APD, compared to a PIN diode, is about ten-fold. The drawbacks of an APD are the high bias ($\approx$ 100V) required and the temperature-dependence in performance. Because of this complication, the APD is envisioned primarily for long distance applications.

III. SHIPBOARD DATA MULTIPLEX SYSTEM (SDMS)

A. SDMS CONCEPT

Numerous sophisticated shipboard electronics have been developed to counter an ever increasingly complex air, surface and undersea threat. Presently, information is transferred between these complex systems through a proliferation of heavy cabling, bulkhead penetrations, junction boxes and switchboards.

It is almost inconceivable to see a reduction in the amount of data exchange between subsystems, but the basic method by which subsystems communicate can be simplified. This method is called the SDMS ... Shipboard Data Multiplex System. It increases data transfer capabilities, reduces costs and simplifies ship-subsystem integration throughout the life of any ship.

Historically, the particular information transfer needs of each electronic subsystem have been met by installing dedicated cabling throughout the hull ... cabling that is unique to a specific set of hardware, configured to meet a specific mission.

Once this mass of functionally dedicated cabling is installed, pulled through cable trays, and fastened to bulkheads, its complexity hinders the rapid and relatively inexpensive reconfiguration needed to keep the ship up-to-date.

Because multiple, hard-wired paths cannot be installed for all signals, the ship's information transfer function is vulnerable to disruption. Conventional wiring often leads to EMI (electromagnetic interference) problems produced by uncontrolled levels of coupling between different circuits whose cables are routed through common cable trays.

The cost of installing all this cable is rapidly increasing because of the high labor costs of design, drafting, cable pulling, connector installation and cable testing. Life cycle costs of cable installation on a DLGN, with nearly 100 miles of cable, not including power and voice cabling, is in the tens of millions of dollars [11].

The most serious problem posed by conventional wiring on ships is that of over-coupling. Ship components are over-coupled in that every exchange in system-to-system interface has an impact throughout the development community. Interface standards do not exist or are not widely accepted. The ship components and the ship design are over-coupled in that changes in subsystem interface characteristics or functional partitioning affect the ship's intercompartment wiring. This over-coupling locks the subsystem and ship design phases closely together and, in effect, leads to premature design freeze. The end result is that the electronics suite is not up-to-date when the ship is commissioned.

Instead of miles of unique cabling that must be specifically designed for each ship, SDMS will meet future information transfer needs with fiber-optic cable ... cable

that will be installed according to a standard plan that does not vary with changes in the ship's electronics suite. With standard fiber optic cabling throughout the ship and standard SDMS interfaces to ship subsystems, adding new equipment will be similar to plugging in standard household items into wiring outlets.

The greatest impact of SDMS is that it will decouple ship subsystems, from each other and from the ship itself. Standard multiplex interfaces will avoid the cost and delay of modifying subsystems to make them compatible. The ability to wire a new ship according to a standard fiber optic cable plan, long before the ship subsystems are fully defined, frees both the ship and the subsystems to develop at their own pace. The ability to overlap these two development cycles will compress ship development schedules and provide ships with more advanced subsystems.

Before discussing the SDMS in detail, it should be noted here that the concept of SDMS is merely "less conventional cable replacing conventional cable." The actual use of fiber optic cabling appears to be a long way off. The purpose of the forthcoming discussion is to show that fiber optics is applicable to the SDMS if given major consideration by the Navy. The Navy's commitment to the application of data bus technology to shipboard internal communication stems from the necessity to reduce cable congestion and weight. SDMS is a general purpose information transfer system intended to take the place of most of the point-to-point cabling and

associated hardware presently used for information transfer aboard naval ships. This relatively new system uses frequency and time division multiplexing of a two-level set of redundant interconnections to provide higher reliability and survivability with lower weight than present point-to-point systems. It is being built by the Autonetics Division of Rockwell International under contract to the Naval Sea Systems Command. It is potentially capable of distributing throughout a ship all forms of periodic and aperiodic signals, either analog or digital.

Two-level multiplexing, wherein user access is provided through remote multiplexers (RMs) which transfer information to area multiplexers (AMs) and thence to a common data bus, allows many access points to be serviced without the attenuation that would result from separate connections to a common data bus. The first stage of multiplexing, consisting primarily of pulse coding in the RMs, is followed by time multiplex transmission to the AMs at baseband. Each AM serves up to eight RMs on a direct basis. Each dual redundant RM is connected to two adjacent AMs as well as to its associated AM to provide increased system survivability.

SDMS provides for interchange of information between AMs by both time-division and frequency-division multiplexing over a five-fold, redundant data bus, under the control of traffic control units (TCUs). Since the five data busses can be used independently and four of the five carrier frequencies can be used for message transmission, as many as

20 separate messages can be transmitted at any given instant. The five data busses interconnecting the AMs are termed primary data busses. Each AM has access to all five busses. As many as 16 area multiplexers per system can be used to support information transfer requirements for ships of various sizes. The Navy considers 16 area multiplexers as "maximum size" and 8 area multiplexers as "normal size". A maintenance unit (MU) is provided for performance monitoring, fault isolation and configuration auditing. The five frequency-modulated carriers, located between 45 and 78.6 MHz, handle data at 1.2 Mbps and are available, one at a time, to each AM. The SDMS design calls for a bit error rate of 10^{-6} prior to error correction procedures. Each primary bus can be as long as 1500 feet (460m). Each area multiplexer stub can extend to 300 feet (≈90m). Therefore, the maximum path length (with one stub on each end of the bus) in the system is 2100 feet (640m) [12].

B. NAVY SIGNAL TRANSFER APPLICATIONS

Before actually considering fiber optics for the Shipboard Data Multiplex System, the NOSC provides one with a thorough knowledge of the methodology required in analyzing fiber optic uses in fleet signal transfer applications [13].

1. Large Ship Signal Transfer Requirements

The first step in the analysis of fiber optics for large ship applications is to identify the information

transfer requirements. The identification of every signal and its classification as to type, bandwidth/data rate, source and destination, and length of cable run is a very large preliminary effort. In order to assure that the entire effort on this task is not expended solely on identifying requirements, several assumptions and decisions were required.

a. The first was to use the CSGN strike cruiser as the specific ship from which to obtain the majority of the data transfer requirements. This ship contains the most modern weapons, communications and navigation equipment and therefore has the most stringent data transfer requirements. A detailed signal analysis, CSGN Preliminary Design Report, Shipboard Data Multiplex/Combat System Feasibility (U), NAVSEC 6179E, October 1976, has been accomplished on the other systems of the CSGN in order to determine the feasibility of the use of the SDMS to satisfy the CSGN data transfer requirements.

b. Where information on specific systems was lacking, other current large ships such as the LHA-platform or DD963 were used as the source.

c. Although specific ships were used to identify information transfer requirements, the results apply equally well to large Navy platforms in general.

d. Where definite information was not obtained, best engineering judgement was used.

2. Present Link Descriptions

The information transfer requirements of a large Navy ship were divided into a number of subsystems to make the analysis more manageable. They include: a) Combat Subsystem; b) Monitored Data; c) Ship Control; d) Interior Voice Communications; e) Exterior Communications.

These subsystems are also helpful in that the systems operate rather independently from one another and vary greatly in the architecture of how equipments are interconnected. Understanding this variation in methods of interconnections enhances the best utilization of fiber optics aboard a large Navy vessel.

3. Fiber Optic Configurations

Each subsystem describes the various possible fiber optic configurations. The advantages and disadvantages of each fiber optic configuration are discussed in terms of: a) performance effectiveness; b) size, weight, power; c) cost, risk.

The recommended fiber optic system includes the optical cable type, optical transmitter, optical receiver and any special components required such as an optic data bus or optical multiplexer.

C. COMBAT SUBSYSTEM

The present combat subsystem for a CSGN is essentially the AEGIS system. In this system, a large number of diverse and remotely located subsystems need to be interconnected.

Cable lengths vary from 20-30 feet for adjacent rooms to 1000 feet for the most remote areas.

It has been shown that the use of SDMS for the CSGN combat system interconnections results in significant weight and space savings. Eighteen miles of conventional cabling will be replaced by seven miles of SDMS cabling. Thirty tons of conventional cabling will be replaced by 13 tons of SDMS cabling and hardware. Furthermore, many CSGN converter devices can be replaced and switchboards reduced in size as a result of SDMS implementation. This combined with high reliability, high survivability and both initial and life cycle cost savings make SDMS very attractive for new large ships.

SDMS makes use of multiplexing and multiple data busses to achieve these savings. Fiber optics is merely a data transmission medium and in many applications requires use of multiplexing and/or a data bus. Therefore, fiber optics and SDMS can complement each other and together arrive at an optimum information transfer system.

The signal analysis identified and partially characterized approximately 1600 signals which were transferred between rooms aboard the CSGN for the combat subsystem. Acceptable signals are those which are insensitive to a 200 μsec (average) transport delay and require less than a 1.0 Mbps information throughput rate. Out of the 1600 signals identified, it was learned that 600 of these signals could not be used in the

SDMS. The remaining 1000 identified as acceptable for SDMS were low bandwidth signals which were shown in previous analyses to be non-cost effective for fiber optics implementation on a one-for-one cable replacement basis. Therefore, multiplexing is essential in reducing the interconnecting cabling and use of a data bus reduces the cabling even further.

A fiber optic bus will reduce weight and volume over a coaxial cable and provide improved performance, reliability and additional bandwidth for future growth. The length of each primary bus for a large ship will be 1000 feet (1/2 km). However, fiber optic bus structures and key bus components such as star and tee couplers are still in their early stages of development.

The remote links of the MUX/Data Bus System include the I/O Unit to the remote multiplexer, remote multiplexer to area multiplexer, and area multiplexer to the data bus links. Presently, a fiber optics link for the area multiplexer to remote multiplexer link for SDMS has been demonstrated in the NOSC lab in San Diego.

It should be noted here that the 600 unacceptable signals to the SDMS could not be used in a MUX/Data Bus System configuration only. A fiber optic cable may still be used in a point-to-point or parallel-to-serial conversion configuration. One example of a benefit in doing this would be in the case of the Naval Tactical Data System (NTDS) where the interconnecting cabling and connectors will be reduced

in size and weight with resultant reduction of cable installation cost. Savings up to 90% in space and 87% in weight have been demonstrated for these types of links.

D. MONITORED DATA SUBSYSTEM

Monitored Data supports the transmission of ordering, indicating and alarm signals. The method of transmission of the monitored data currently used on most ships consists of individual hard-wired circuits using twisted pair wire for the transfer of each signal. A more efficient method of data transfer than point-to-point would be to multiplex many of these low data rate signals and to make use of a data bus to transverse the many diverse locations required to be monitored.

Typical types of transferred signals include:

1. engine, propeller and rudder orders.
2. gyro heading, roll, pitch and speed.
3. wind direction and speed.
4. propulsion plant water pressure and temperature.
5. damage control alarm signals; compartment temperature, compartment flooding, vent status, fan and pump controls.
6. sonar and fire control cooling water status.

The entire 2058 identified low band-width signals of the monitored data subsystem can be used in the SDMS. These types of signals were also shown to be non-cost effective for fiber optics implementation on a one-for-one basis.

Once again, multiplexing and use of an optical data bus is essential to appreciably reducing the interconnecting wiring. This is even more desirable if the combat subsystem is also to be handled by a MUX/Data Bus System since many of the major bus components would be shared.

If the MUX/Data Bus System was used for the monitored data subsystem, then the fiber optic candidates would be the same as discussed in the combat subsystem.

E. SHIP CONTROL SUBSYSTEM

The ship control subsystem supports the command stations in directing the underway operations of the ship. Ship control includes ship handling, navigation and ship command. The primary locations involved in ship control are the pilot house, the bridge wings, the enclosed operating stations, the steering gear room, the chart room and the combat information center. The typical types of signals to be transferred include: 1) engine orders, propeller revolutions; 2) rudder orders, rudder angle; and 3) steering pump status.

The primary locations involved in this sub-system are relatively close and the number of signals to be transferred are relatively few ($\approx$ 63). The use of fiber optic cabling for ship control signal transfer on a one-for-one basis is not cost effective and is therefore not recommended. The limited data transfer requirements for this subsystem alone does not cost effectively support an independent MUX/Data Bus System. These signals could be incorporated into the

previously mentioned combat subsystem's MUX/Data Bus without significantly raising the maximum system data rate or without introducing any additional major components.

F. INTERIOR VOICE COMMUNICATIONS SUBSYSTEM

Interior voice communications are required for the exchange of information between ship stations. The three types of voice communication required aboard ship are point-to-point, net conference and public broadcast.

The baseline system from which the majority of the interior voice communications requirements will be derived is the AN/STC-1 interior voice communications system which is presently aboard the LHA-1 class ships. The STC-1 system consists of two interconnected switching centers to which all the voice user terminals are connected. In the event of failure of one of the switching centers, the other can support some of the terminals assigned to the failed unit.

It is interesting to note here, that a quick reaction Navy Science Assistance Program (NSAP) project, installed a fiber optic telephone system on board the USS LITTLE ROCK. The new telephone system provided a new capability for quick, efficient and safe transfer of sensitive information. The phone configuration provided communications between six stations; one each located in flag plot, intelligence, chief of staff, SUPRAD, and two in the combat information center.

The entire project was accomplished within a strict six month schedule with the initial system burn-in occurring after installation and deployment on board the USS LITTLE ROCK. At the end of the burn-in period (December 1973), minor repairs and modifications were made in the switching and dialing logic circuits to improve performance. Since December 1973, only normal maintenance was required (replacement of two microswitches, two off-the-shelf power supply modules, and one fiber optic cable set severed by accident). COMSIXTHFLT favorably commented on this new technology. The entire system is presently in storage at the NOSC in San Diego.

The primary links in the interior voice system consist of 360 voice terminals connected to a centrally located switching center. The major options for fiber optics implementation in the interior voice system are:

1. A one-for-one fiber optic cable replacement of the 360 cables of the STC-1 system. However, the net savings in weight and volume of cable for this application is minor. The cable savings are offset by the addition of a fiber optic driver and receiver for each cable. Performance advantages are minimal and cost of a retrofit fiber optic system is high.

2. Integration of the voice transfer links of the STC-1 into the combat system MUX/Data Bus System. Presently, the STC-1 system contains 20,700 pounds of cabling. This could be reduced substantially by the use of the MUX/Data Bus

System to transfer the data between the terminals and the switchboard. This assumes that the MUX/Data Bus System is installed aboard the ship and the bandwidth is available. Bandwidth should not be a problem since the voice terminals are not operated on a full time basis and bus bandwidth is only affected by terminals in use. At this time, additional hardware will be costly. Each voice terminal located in a remote compartment requires its own interface module containing an analog-to-digital and digital-to-analog converter.

3. Redesign the present system to a fiber optics interior voice communications system. The STC-1 system was designed for use with an architecture that was compatible with conventional cabling. In order to arrive at the most efficient system with inter-unit fiber optic cabling, a redesign of the entire interior voice system is required. The new system would include the addition of many functions not presently accomplished by the STC-1. For example:

a. Fiber optic bus architecture reduces cable requirements and saves weight and volume.

b. Utilization of fiber optics would presently assure RF TEMPEST secure communications. Developing, intrusion resistant fiber optic channels show promise for future transmission of clear voice traffic.

c. An intrusion resistant fiber optic bus system for the interior voice communications system could be modified to include transmission of secure voice and other classified data aboard ship.

d. Due to the high bandwidth available with the fiber optic cable, classified high data rate digital signals and video data could be included to make this system a general purpose shipboard data transmission system for all classified data. However, the cost of development of such a general purpose system is high since it involves a multi-year research and development (R&D) effort.

G. EXTERNAL COMMUNICATIONS SUBSYSTEM

The modern shipboard communications system is a complex arrangement of receivers, transmitters, modems, crypto and terminal equipment. These equipments are interconnected by switchboards, patch panels and a large amount of conventional cable. The majority of naval vessels have manual switchboards and patch panels. The LHA class contains the most automated communications equipment and remotely controlled switching matrices. Therefore, this system will be used to provide an analysis between the potential fiber optics application and the present exterior communications subsystem.

The signal transfer activities of the exterior communications subsystem are basically restricted to three areas of the ship:

1. the communications center (including crypto area),
2. the radio switching receiver room, and
3. the transmitter and transceiver room.

The cables interconnecting these areas range in length from 200-300 feet, while within each area, the cable length

averages about 50 feet. The signals consist of teletype (TTY), low data rate digital (up to 32K bps), audio frequency, and control signals. The LHA platform has a black digital switch with a 75 x 75 port capacity and three black analog switches with a 225 x 225 total port capacity. Each port consists of six wires capable of handling the communication signal and associated control and status signals.

Potential fiber optic uses for the external communications subsystem are:

1. <u>High and Low Power RF Signals</u>

Presently, the fiber optics cable is not capable of carrying high power RF signals. Low power RF radio signals are feasilbe up to approximately 200 MHz over short lengths. The lead-in transmission line spans from the antennas mounted high on the ship's structure to the radio receiver room and usually consists of a coaxial cable. The most common antenna and lead-in transmission line fault is low resistance to ground. These resistance paths are created by moisture, salt spray, dirty insulators, corrosion or a breakdown in the coaxial cable dielectric. A fiber optic lead-in cable could be made entirely non-metallic. This would eliminate many of these problems and also make the receiver lead-in cable immune to RF coupling from the ship's transmitting antennas. However, this is not a serious problem. The energy coupling between the receiver/transmitter antennas is a far greater problem.

Several of the disadvantages are that some form of receiver and fiber optic modulator must be located at the antenna and, in addition, primary power must be provided to this remote electronic equipment.

2. <u>Black DC and Audio Link</u>

These signals could be transferred via the MUX/Data Bus System or via point-to-point fiber optic cable. The MUX/Data Bus System would route the signals out of the compartment through other areas of the ship via the area multiplexer and data bus and finally back to the originating compartment. The signals must also be digitized to the bus data rate. Another consideration is that the Navy shipboard communications system has traditionally retained its independent nature and opposition to a general data transmission system may be strong.

The use of fiber optic cable on a one-for-one basis was shown in the previous CSGN analysis to be non-cost effective at the present time. The cost and complexity of the numerous additional fiber optic drivers and receivers required for this installation would offset the savings in cable weight and volume. In order to realize any appreciable benefits from fiber optics in the shipboard exterior communications subsystem, development of the following new optical components is required:

a. a fiber optic patch panel,

b. an optical switching unit, and

c. an optical multiplexing unit.

3. <u>Red DC and Secure Voice Systems</u>

These signals could be transferred by means of a data bus or by a point-to-point fiber optic cable. Point-to-point fiber optic cable systems for this particular application could be built with fiber optic components available today.

In order to reduce cable weight and volume requirements, a bus structure is necessary. However, fiber optic bus systems are still in the process of being developed, since key bus components, such as optical couplers are still in their infant stages of development.

H. FURTHER STUDY

From the previous discussion of the ship's subsystems, it is reasonably safe to say that there are major signal transfer areas that seek fiber optic attention. In summary, they include:

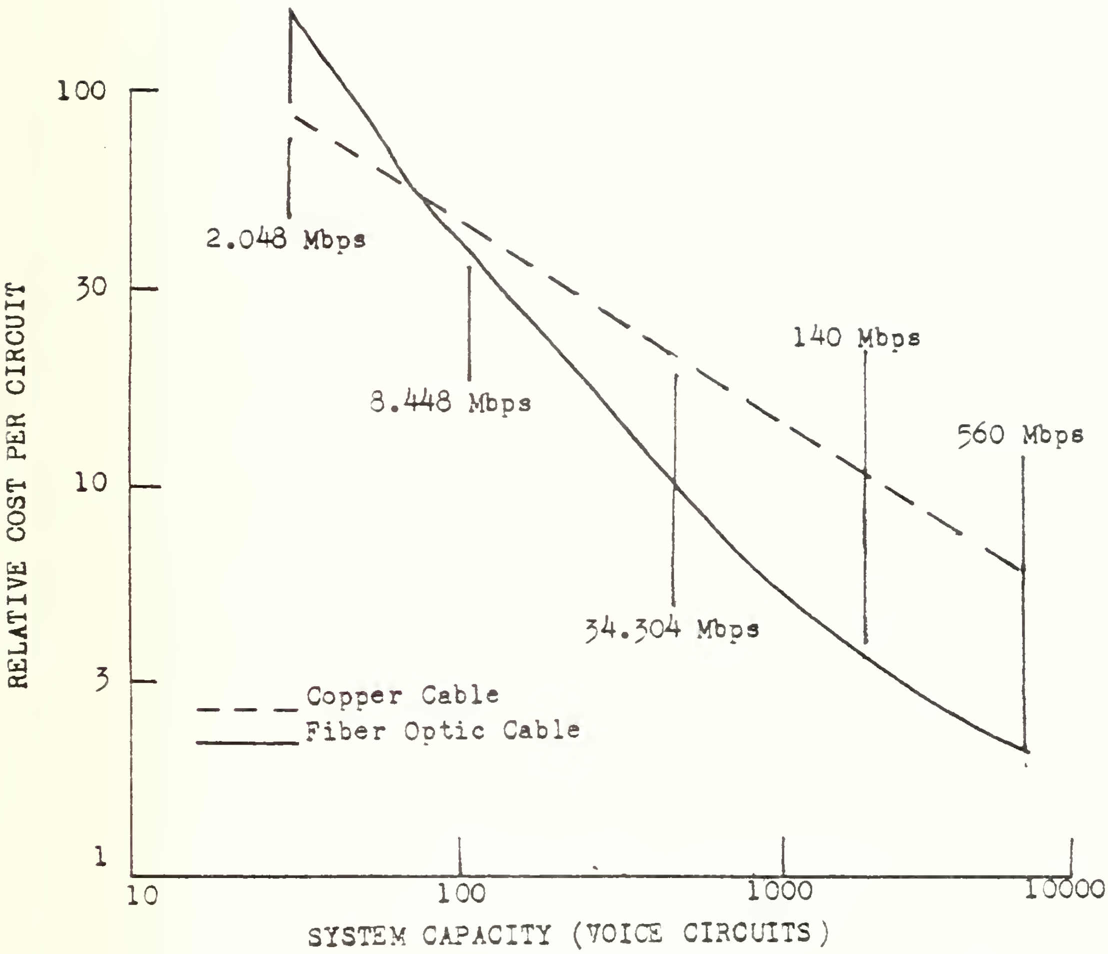
1. a primary data bus,
2. 200 microsecond transport delay signals such as video, radar and CRT sweep signals,
3. secure communications,
4. a fiber optic patch panel for the technical control facility,
5. NTDS fast/slow interface using fiber optic components, and
6. the use of fiber optics and multiplexing to solve the rotary joint problem.

IV. ECONOMIC ANALYSIS

A. GENERAL

Giallorenzi [3] states that the economic viability of fiber optics relative to competing technology is the single biggest determinant of the degree of final utilization. Several projections of cost for fiber optic systems have been undertaken and the results of these studies all indicate that fibers will offer economic advantages when data rates exceed roughly 8 Mbps. Cost predictions are difficult to accurately perform for new technologies and are strongly subject to the assumptions made. Even though most of the projections to date are favorable, one must consider the possibility of systematic projection errors caused by common biases held by those performing the projections. Thus qualified, projections performed to date predict the attractiveness of fiber optics and thus justify continued involvement in this technology by the telecommunications industry.

An item by item comparison of individual costs, e.g., of cable, installation, repeaters, repeater housings, and repeater-site provisions was recently performed by Kao and Collier [14]. Their analysis did not include the costs of multiplex equipment which would be common to both metallic and fiber optics systems with the same capacity. Their results are presented in Figure II. Typical duct installation costs are included, giving some advantage to fiber



NOTE: BASED ON ROUTE
OF 50 100km
NO MULTIPLEX INCLUDED

Fig. II. COMPARISON OF THE COST PER CIRCUIT USING OPTICAL FIBERS AND COPPER CABLE AS A FUNCTION OF SYSTEM CAPACITY (after Ref. [3])

optics because of their smaller size but do not allow for the very major savings which could arise when ducts are heavily congested and the use of fiber optics could help avoid the need for costly new ducts. The smaller size and light weight could revolutionize installation techniques and permit a much greater usage of duct space.

A second analysis performed by Colavito, Catania and Pellegrini [15] reaches basically the same conclusion as Kao and Collier and is presented in Figure III. Cable, regenerator, and line terminal equipment costs are included in this study. Above approximately 15 Mbps, fibers showed economic advantages over metallic cables. These authors also concluded that at data rates of 8 Mbps, under certain circumstances, fibers would be economical. For lower bit rates, the cost of copper cable was concluded to be so low that it overcomes the cost of additional repeaters. The difference in cost between metallic and fiber systems largely results from repeater costs. In Figure III the upturn in the projections above 200 Mbps is attributed to the requirement for additional repeaters. Data points are also included for higher bandwidth graded index and single mode fibers. This data indicates that when fiber repeater spacing is determined by fiber loss (assume 5 dB/km) and not bandwidth, then fibers retain significant cost advantages over metallic cables.

These authors also include projected fiber fabrication costs for various types of optical fibers. Fiber costs are

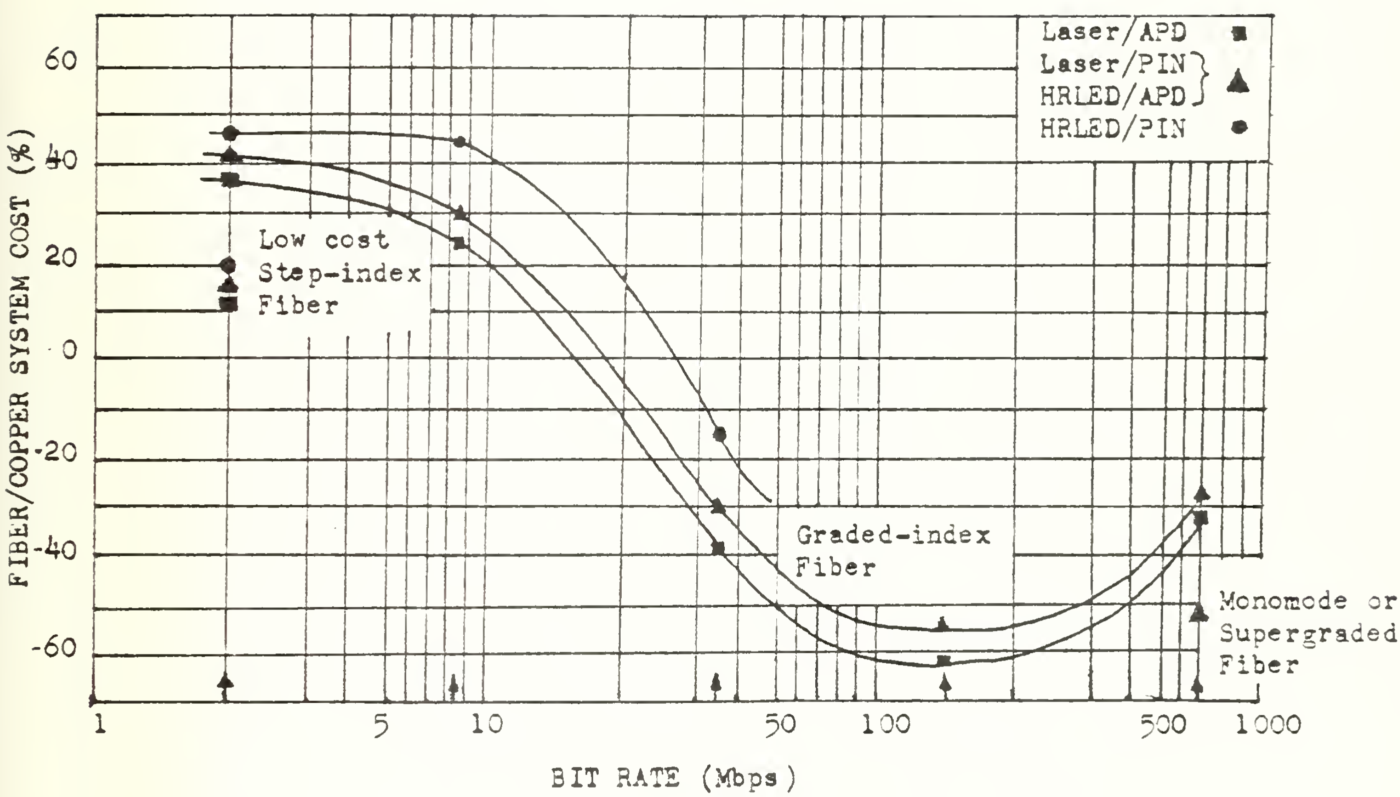


Fig. III. COST RATIO OF FIBER TO COPPER SYSTEMS AS A FUNCTION OF BIT RATE (after Ref. [3])

projected to be about \$0.05-\$0.08/meter in production quantities of ($\sim 10^4 - 2x10^4$ km/yr) which is lower than that projected by Corning (\$0.10/meter for production rates of 10^5 km/year) [3]. Cabling cost is seen to determine the cost of the cable which strongly suggests the development of a universal cable incorporating the highest bandwidth fibers that are available. One cable could then be used both for low and high bandwidth applications and the increased use of a single cable type should minimize production costs.

A comparison of optical and milimeter systems is difficult because the cost of waveguide and installation of millimeter waveguides is not accurately known. Colavito, Catania and Pelligrini [15] also compared millimeter waveguides and low dispersion optical fibers. A 50 fiber cable and 50 RF channels were assumed. The link length was assumed to be equal to the regenerator spacing of the millimeter guide; a length assumed to require 4 optical regenerators (about 7 dB/km fiber) for each fiber channel. With these assumptions, no advantage could be realized using one or the other approach. However, with the development of single fiber, spectral division multiplexing techniques, i.e., the use of different optical wavelengths for carrying the various information channels, it may be possible to employ a single fiber to carry the postulated 50 channels. In this event, cost considerations would strongly favor optical fibers over millimeter wave approaches.

From the analyses presented, continued investment by the telecommunications industry will lead to economic advantages in the application of fiber optic systems, and it can only be concluded that fiber optic systems will be implemented. Fiber optics provides both a low cost, very high capacity, longline transmission capability, and a versatile short distance distribution capability. It is technically and economically competitive in both of these areas.

It can be concluded that toward the middle to end of the 1980's, optical fiber systems are likely to present technical and economic advantages that render them more attractive than copper cable and perhaps millimeter wave systems for public telecommunications and military uses. Trends in the development of the fiber optics market predict a $1.5 billion market by 1990. This indicates initial growth in applications where the unique advantages of fiber optics justifies its slightly higher price. Explosive growth is projected beyond 1980 as optical fibers are incorporated in prototype and production systems. The evolution and projected makeup of the fiber optics market are shown in Figure IV [3].

The demand for communications bandwidth has grown tremendously over the past decade and continues to increase, taxing present capabilities close to or beyond their limits. Bandwidth and the economies of large bandwidth links present fiber optical communications a unique opportunity in evolving markets. Additionally, technologies to supersede fiber optics in terms of capabilities and economics do not seem forthcoming.

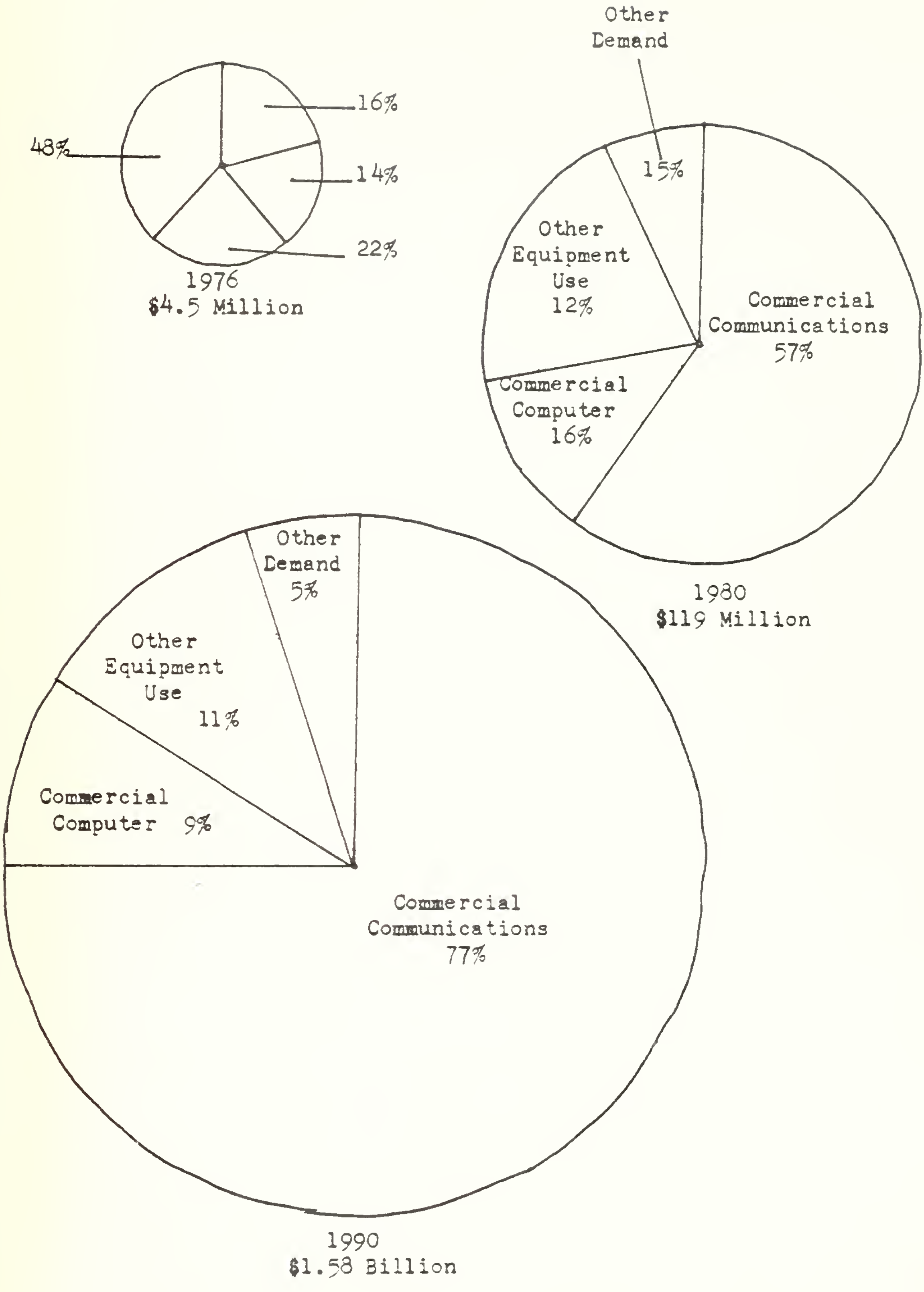


Fig. IV. EXPECTED WORLD-WIDE FIBER OPTICS MARKET (after Ref. [3])

B. FIBER OPTIC CABLE AND COAXIAL COST COMPARISON

Comparing cost data for two different technologies, both performing the same function is a valid method of cost analysis. A study conducted by Jones, et al. [16] produced a cost comparison, on a cost element by element basis, between coax and fiber optic technologies. The basis for the comparison was the analogy method of cost estimating. The analogy method relies upon persons knowledgeable in performing a task in one technology so that they can be questioned about the level of effort (in dollars, man-hours, etc.) required to perform the same task using a substitute technology.

Cost data is available for equipment or systems using coax cable. Similar cost data for equipment or systems using fiber optic cable is not necessarily available since fiber optics is still basically a new technology and only a limited cost data base has been collected. This lack of available cost data requires that many of the fiber optic costs be "best estimates". In order to facilitate a best estimate approach to determining costs, each fiber optic cost was formulated as a multiple of coax cost for the same cost element.

With the use of known coax cost data for a specific task, a cost comparison for the same task can be determined in order to transition between two technologies. Because of the uncertainty associated with some costs, the fiber optic

estimated cost is presented in the form of a cost range; a minimum value and a maximum value. Uncertainty associated with any cost element is an indication of areas for future investigation. As the fiber optic technology advances, these first approximation costs will require refinement. It can be expected that over time, a future analysis effort will be required to revise both the minimum and maximum values of the estimated cost range.

Table I [16] contains the authors' first approximation to the "best estimate" cost comparison between fiber optics and coax. The table is a good tool for a project manager because it takes the cost comparison from research and development to non-recurring investment and finally to operating and support. As an example of the method used to develop a first approximation cost estimate, consider cost element 3.1.6.2 CONTRACTOR SITE/SHIP/VEHICLE CONVERSION during production. The table shows that the superior fiber optic performance characteristics listed should be considered and utilized during the development and design effort; to reduce the subsequent installation (conversion) effort and cost. The cost coefficients for each cost element were determined by dividing the cost of the fiber optic alternative of the specific cost element by the cost of the coax cable alternative of the same element. As seen in the table, the upper limit for element 3.1.6.2 is 1.0 while the lower limit is 0.7.

The study estimates that the cost of performing the task identified by cost element 3.1.6.2 could range between the limits of:

1. the task performed using fiber optics with a minimum cost of 70 percent of the same task performed using coax.

2. the task performed using either fiber optics or coax would have a maximum cost equal to the cost of coax.

The major cost elements are listed as follows:

1.2.1.2	- engineering
1.2.1.4	- contractor development tasks
1.2.1.5	- test support
1.2.1.8	- peculiar support and test equipment
1.2.1.10	- general and administrative
1.2.2.3	- government tests
2.1.3.4.	- manufacturing support equipment
2.1.4	- technical support
2.1.5	- initial spares and repair parts
2.1.6.3.2	- maintenance training
2.1.10	- peculiar support and test equipment
2.1.12	- general and administrative
2.2.2.2	- training devices and equipment
2.2.2.3.2	- maintenance training
2.2.2.3.3	- instructor training
3.1.1	- manufacturing
3.1.2.1	- purchased equipment and parts
3.1.2.2	- subcontracted items
3.1.2.3	- other material

3.1.3 - sustaining engineering

3.1.6.2 - site/ship/vehicle conversion

3.1.6.3 - assembly, installation and checkout

3.1.8 - general and administrative costs

4.1.6 - other operations costs

4.2.1.1.1 - organizational maintenance personnel

4.2.1.3 - support equipment maintenance

4.2.2.3 - spare parts and repair material

4.2.2.4.1 - inventory management

The significance of the comparison is that a general cost estimation process has been developed to permit cost estimation and direct comparison of two alternative technologies. The basis for this estimation was a combination of knowledge gathered during interviews, research, intuition and judgment. All estimation concerns judgment. The purpose of this approach is to structure and direct the estimation process so that multiple expert judgments can be utilized and synthesized to a significant estimate.

Table I

COST ELEMENT COMPARISON

RESEARCH AND DEVELOPMENT

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
1.2.1.2 Full Scale Development Contractor Engineering	1.0	*	Since fiber optics is an infant technology there will undoubtedly be a large effort expended to develop the potential use for fiber optics. The scope of this effort will be dependent upon both Government and industrial support or interest in the technology.
1.2.1.4 Full Scale Development Contractor Development Test	1.0	*	In anticipation of maximum benefit from a fiber optic Research and Development program, the contractor must conduct an exhaustive test program. This type of effort, properly conducted, has a historically high cost.
1.2.1.5 Full Scale Development Contractor Test Support	1.0	*	This cost will be higher for fiber optic for the same reasons as noted in cost element 1.2.1.4. Test support will be in conjunction with the effort identified in cost element 1.2.2.3.

Table I (Continued)

RESEARCH AND DEVELOPMENT

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
1.2.1.8 Full Scale Development Contractor Peculiar Support and Test Equipment	1.0	2.0	Research and Development of peculiar support and test equipment is not expected to be a major effort. The anticipated requirements for support and test equipment that are unique or peculiar to the new fiber optic technology should be minimal.
1.2.1.10 Full Scale Development Contractor General and Administrative	1.0	1.8	The level of effort of Research and Development in the fiber optic technology is expected to be larger than a coax technology program. There is existing a data base for coax technology but the data base for fiber optic technology is only being developed at this time.
1.2.2.3 Full Scale Development Government Test	1.0	*	The culmination of an extensive Research and Development program are the purposeful tests. Expectations for future use of fiber optic technology dictates a major test and evaluation program. This effort will be much in excess of test programs for coax cable.
		*	During the Research and Development phase of a new program the ceiling cost is primarily limited by the funding available. The present interest in fiber optic technology is quite strong and the program is expected to grow rapidly.

Table I (Continued)

INVESTMENT (NON-RECURRING)

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
2.1.3.4 Contractor Manufacturing Support Equipment	1.2	1.8	Manufacturing equipment for use with coax cable presently exists. To establish the capability of working with fiber optic cable, new support equipment will be required. This additional capability will cause an increase in the fiber optic support equipment cost.
2.1.4 Contractor Technical Support	0.6	1.0	The replacement of coax cable with fiber optic cable will be contingent upon several factors. One primary consideration will be successful testing during the Research and Development phase of a program. If fiber optic cable is used in aircraft production it will only be after successful early testing and the assumption is then made that follow-on testing will be minimized or possibly eliminated.
2.1.5 Contractor Initial Spare and Repair Parts	0.8	1.6	The advances in the fiber optic state-of-the-art and the ability of industry to economically mass produce cable, transmitter module and receiver modules control this cost element range.

Table I (Continued)

INVESTMENT (NON-RECURRING)

Cost Element	Fiber Optic Cost		Remarks
	Minimum	Maximum	
2.1.6.3.2 Contractor Initial Maintenance Training	1.2	2.0	Maintenance training for fiber optic equipment or systems will be in excess of the training presently conducted on systems using coax cable. The excess cost exists because a maintenance technician would be knowledgeable in coax cable maintenance but fiber optic technology is a new requirement in addition to this present ability.
2.1.10 Contractor Peculiar Support and Test Equipment	1.2	1.8	Maintenance and support equipment unique or peculiar to an equipment or system using fiber optic cable will be required. This requirement is in addition to the existing requirement for coax cable maintenance and support equipment already in use.
2.1.12 Contractor General and Administrative	0.9	1.0	Fiber optic technology should cause a production effort to be less than a similar coax system. Therefore, the General and Administrative costs would be slightly less for productive using fiber optic technology.

Table I (Continued)

INVESTMENT (NON-RECURRING)

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
2.2.2.2 Government Training Devices and Equipment	2.0	3.5	The knowledge of coax cable technology exists within the appropriate Navy schools today. Adding fiber optic technology to the existing school curriculum will generate a cost that is in excess of any cost associated with coax cable training.
2.2.3.2 Government Initial Maintenance Training	1.1	1.8	The Government cost to train both maintenance personnel (cost element 2.2.2.3.2) and instructor personnel (cost element 2.2.2.3.3) is directly related to the length of time required for the training. Fiber optic technology will require training in excess of that required presently by coax cable technology.
2.2.2.3.3 Government Initial Instructor Training	1.1	1.8	

Table I (Continued)

INVESTMENT (RECURRING)

Cost Element	Fiber Optice Cost Minimum	Fiber Optice Cost Maximum	Remarks
3.1.1 Contractor Manufacturing	0.8	2.0	As fiber optic technology advances and additional applications are discovered, the cost of material will probably decline. However, at this point in time the production base for fiber optics is limited, thereby keeping the cost of fiber optics above the cost of coax.
3.1.2.1 Contractor Production Purchased Equipment and Parts	0.8	2.0	Large quantity usage and mass production is expected to reduce the cost of fiber optic components to a level below that of similar coax components. The present demand for fiber optics is limited, therefore the cost of components is higher than coax.
3.1.2.2 Contractor Production Subcontracted Items	0.8	2.0	Increased applications of fiber optic technology coupled with a greater usage demand should reduce the cost of fiber optic components. At some point in future time, it is expected that fiber optic components will cost less than their coax counterparts but presently fiber optic component costs are generally higher than coax.

Table I(Continued)

INVESTMENT (RECURRING)

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
3.1.2.3 Contractor Other Production Material	0.8	2.0	Raw material for the manufacture of fiber optic cable is readily available and mass production should decrease the cost of fiber optic components. Mass production can not begin until the demand for fiber optic increases. Copper is becoming a scarce commodity and therefore the cost of coax is expected to increase in the future.
3.1.3 Contractor Sustaining Engineering	0.7	0.9	The engineering costs associated with future modification or field changes of a fiber optic equipment or system will be less than those costs associated with a coax system. The use of fiber optic technology would place fewer restrictions on design engineers.
3.1.6.2 Contractor Site/Ship/ Vehicle Conversion	0.7	1.0	The physical characteristics of fiber optic cable allow its installation in places not accessible with coax cable. This attribute will allow design engineers to design fiber optic cable routes at a lower cost than coax cable.

Table I (Continued)

INVESTMENT (RECURRING)

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
3.1.6.3 Contractor Operational Assembly, Installation, Checkout	0.85	1.0	In conjunction with the reduced cable route design complexity, checkout will be simplified for fiber optic cable systems.
3.1.8 Contractor General and Administrative	0.9	1.0	Fiber optic technology should cause a production effort to be less than a similar coax system. Therefore, the General and Administrative costs would be slightly less for production using fiber optic technology.

Table I (Continued)

OPERATING AND SUPPORT

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
4.1.6 Government Opportunity Cost	1.0	1.0	Reliability of a fiber optic cable system is expected to be higher than a similar coax system. If this assumption is valid, then the down time of an aircraft due to electrical problems will be less. However the daily or differential opportunity cost of a down aircraft is the same regardless of the type cable system. The cost differential is identified where one system has fewer down days.
4.2.1.1.1 Government Organizational Maintenance Personnel	0.7	0.9	The assumed reliability of fiber optic equipments or systems causes this cost to be less than a similar cost for a coax system.
4.2.1.3 Government Support Equipment Maintenance	1.0	1.5	Support and test equipment presently in the inventory will remain even after the introduction of fiber optic cable. The additional cost will be recognized as that required to maintain the unique or peculiar support and test equipment which was developed under cost element 1.2.1.8.

Table I (Continued)

OPERATING AND SUPPORT

Cost Element	Fiber Optic Cost Minimum	Fiber Optic Cost Maximum	Remarks
4.2.2.3 Government Spare Parts and Repair Material	0.7	0.9	The assumed reliability of fiber optic equipments or systems should reduce the cost of repair parts consumed during maintenance.
4.2.2.4.1 Government Supply Inventory Management	1.1	1.3	Coax system components are already a part of the supply system. There will be a cost associated with introducing the new components of the fiber optic technology.

C. EFFECTIVENESS COEFFICIENTS

McNair [17], in the A-7 ALOFT project, provides us with a coefficient of effectiveness where 1 is the value of conventional cable. When the values listed are less than 1, then fiber optics are considered advantageous. On the other hand, when the values equal 1 or are greater than 1, then fiber optics have no advantage or are disadvantageous respectively over conventional wiring. The following table is provided:

Values of the Coefficients of Effectiveness

	A	B	C	D	E	F	G	H
EMI	.7/.8	.8	.7/.8	.7/1	.9/1	.8/1	1	.95/1
EMP	1	.95	.8/1	1	.95/1	1	1	.95/1
SIZE	.7/.8	.7/.8	.7/.9	.7/1	.95/1	.95/1	.99/1	.98/1
WEIGHT	.7/.8	.7/.8	.8/.9	.8/1	.95/1	.1	.98/1	.98/1
HAZARD	1	1	1	1	1	.95	1.05	1
DIELECTRIC ISOLATION	.9	.95	.9	1	1	1	1	.98

A = missiles
B = satellites
C = aircraft
D = drones

E = shipboard equipment
F = control equipment
G = communications networks
H = secure communications

From the chart, it should become obvious that in 97.9% of the cases presented, fiber optics were equal to or more advantageous than conventional wiring.

D. FIBER OPTIC MARKETING

Most of the market research on fiber optics alludes to five main end use markets: telecommunications, CATV, EDP, industrial and military. By 1990, these five markets should represent a total market of over $1.5 billion. The application of fiber optic technology to EDP, industrial and military markets represents the greatest opportunities for all of the second tier fiber optic companies. It should be noted that while the telecommunications market segment is the largest, it will only permit a limited number of competitors due to the present, dominant position of a few companies. Therefore, second tier companies will be vying for the estimated $119 million market in 1980 and the $1.5 billion market in 1990.

The year 1977 was just the beginning for off-the-shelf fiber optic data transmission systems. Custom systems are still the mainstay of the fiber optic data transmission field, but the trend is heading toward off-the-shelf hardware. Recently, new ready-to-use systems have been introduced, requiring only connection to power sources and single lines.

The cost problems of fiber optic components seems destined to solve itself by increased volume production. In 1965, fiber technology represented a 1 million dollar market. As stated earlier, projections for 1980 have already risen from 86 million to 119 million and to a

1.5 billion dollar market for 1990. It is also projected in the 1980-81 time frame that graded-index fibers with under 50 dB/km loss and greater than 500 MHz bandwidth could cost as little as 5 cents per meter in 500,000 km lengths. Projected costs are illustrated in Table II [18].

Table II

FIBER OPTIC COMPONENT COSTS (after Ref. [18])

Limited Quantity Buys	Currently Available 1976-78	Projected Costs 1980-85
Standard Lightweight Cables		
Medium loss bundle cables	2.50/meter	.6/meter
Plastic Clad Silica Single Fiber Cables	.5 /meter	.2/meter
Connectors for Bundle Cables		
Single Channel	2.50/unit	1.50/unit
Multi-Channel 8 channels	50. /unit	20.00/unit
Connectors for Single Fiber Cable		
Single Channel	30. /unit	15.00/unit
Multi-Channels	250. /unit	100.00/unit
Transmitters		
LED for Bundle Cables	36. /unit	5.00/unit
LED for Single Fiber Cables	100. /unit	25.00/unit
Injection Laser Diode for Single Fiber Cables	200. /unit	75.00/unit
Receivers		
PIN Detector for Bundle Cables	25. /unit	5.00/unit
PIN Detector for Single Fiber Cables	82. /unit	15.00/unit
APD Detector for Single Fiber Cables	150. /unit	50.00/unit
Couplers		
16 part radial coupler for bundle cables	800. /unit	250.00/unit
16 part radial coupler for single fiber cables	1600. /unit	400.00/unit

Projected Costs are based on the estimated market potential of fiber optics. These costs may vary due to a delay in establishment of a full production base of this technology.

V. ADVANTAGES OF FIBER OPTIC SYSTEMS

A. GENERAL

The following discussion describes the array of inherent advantages of data transmission systems implementing fiber optic components. It appears that the general trend in military communications is toward an increase in data rate along with a conversion to digital communications. Digital communication is also the preferred means for accomplishing the overall objective of total security for all voice, data, and record traffic within the Department of Defense.

B. SECURITY

A majority of needs are associated with the security category, which is of prime importance in any military application. The least secure military communication means is radio, because the signal can be intercepted very easily. Twisted pair or field cable is more secure, being designed not to radiate, but it is fairly easy to pick up stray radiation. Coaxial cable is somewhat more secure, since the outer sheath significantly reduces the leakage radiation, but sophisticated equipment can pick up the small amount of leakage that does exist. In high security situations, present procedures are to continually monitor the cable with closed-circuit TV or armed personnel, or to use a very expensive intrusion-proof cable.

Optical fibers offer several advantages in security, since optical fibers are non-conducting and optical radiation is easily shielded. Thus, it is virtually impossible to monitor signals without coupling into the fiber. Greater security can be provided with the addition of optical alarms.

Since interception involves coupling, security of a fiber channel can be detected; this is not the case with radio channels. Whenever a twisted-pair, coaxial cable, or optical fiber is tapped, part of a transmitted signal will be reflected back to the source. By using reflectometry techniques, the time delay to each tap could be measured. Mismatches, appearing where unauthorized, indicate potential security breaks, and appropriate action is then taken. This technique depends upon the resolution with which the delay can be measured. Although impractical with twisted-pair and marginal with coaxial cable, the distance equivalent to this delay can be resolved to within a few inches with optical fibers because of their wide bandwidth.

Several applications under the security category involve protection of sensitive information in large-area fixed installation situations such as base communication systems and computer-to-computer links. Security for these military communication situations is provided by concentrating the processing of such information to a physically secure limited exclusion area from which all emanations, both conducted and radiated, are maintained below certain acceptable levels. Communication between two such areas is conventionally

accomplished by encryption of the sensitive data so that it can be sent "in the clear" over non-secure transmission means.

The use of optical fibers offers a secure path over which sensitive data may be transmitted directly, thus obviating the need for COMSEC equipment and the associated account and key maintenance that can become burdensome and expensive. Some of the reasons for optimism include the case with which passive emanations can be attenuated, the easy concealment possibilities, and predictability of the error rates for any given power available to an intruder.

C. HIGH CAPACITY

A significant number of identified needs is associated with high capacity, whereby a greater data volume can be carried by a single channel. The suggested needs include those in the video transmission, computer and multiplex areas. Projected transmission rates for such areas in the near future are shown in Table III [7]. Computer-to-computer messages are expected to be transmitted via input/output devices at speeds of 4.8 Kbps or 307 Kbps, depending on the particular devices. Because of the increased utility of computers, however, the need for direct memory-to-memory transfer will soon prevail. At present, a typical word length is 32 bits and the memory cycle time is one microsecond, resulting in a required transmission rate of 32 MHz. When the cycle time drops to 500 nanoseconds in the 1980's, required rates of 32-64 Mbps may not be unusual.

Table III

DATA RATES FOR DIFFERENT SERVICES (after Ref. 7])

SERVICE	REQUIRED DATA BASE 1970's	1980's
High quality voice	32 kb/s	16 kb/s
Facsimile	32 kb/s	32 kb/s
Record Traffic	4.8 kb/s	4.8 kb/s
Computer-to-computer	4.8 kb/s	307 kb/s
Digital TV	36 Mb/s	6.6 Mb/s
Teletype	110 b/s	—
Videophone	1.5 Mb/s	1.5 Mb/s
Computer-memory-to-computer-memory	32 Mb/s	50 Mb/s

These rates fall clearly within the capability of fiber optics technology. Use of fiber optics will provide benefits in several ways:

1. for a given distance, optical channels provide wider bandwidth,

2. for a given bandwidth, optical fibers can carry signals further without the need for repeaters and equalizers, and

3. the bandwidth capability of fiber optics allows consideration of serial rather than parallel data transfer with its attendant cost effectiveness.

If pulse code modulation (PCM) is used, high quality color video displays with a 48 dB signal-to-noise ratio will require a rate of 72 Mbps. However, picture coding techniques currently in development should reduce this requirement to 6.6 Mbps in the 1980's. The use of optical fibers will allow multiplexing of more of these video channels than can be accommodated over conventional wire channels.

Multiplex techniques are generally used to pack as many channels of information as possible into the available bandwidth of a given transmission channel. When a new transmission technique offers wider bandwidth capability, the multiplexing techniques will advance to meet the offered challenge. Thus, irrespective of the technique, the use of optical fibers will allow a quantum jump in the number of multiplexed channels, limited only by the trade-offs between various multiplexing techniques.

D. SIZE AND WEIGHT

Other identified needs are associated with the size and weight reductions of fiber optics over conventional techniques. The physical dimensions alone offer an approximate 2:1 reduction in size and weight over conventional coaxial cable. When the added channel capacity of fiber optics is considered, the effective reduction is considerably greater. The size/weight reduction offers considerable cost savings in other areas as well. The logistics necessary to transport material are a direct function of weight; therefore, optical fiber components can be transported, stored, set up and torn

down using fewer men and vehicles than is possible with wire systems. This becomes especially significant for tactical situations, in which system mobility is largely dependent upon the size/weight of components. Even in fixed-base applications, the ease of repair and maintainability become more realizable with components that are lighter and less bulky.

1. Installation Costs

The small size and low weight of fiber optic cables naturally helps to keep manpower costs of installation down. The U. S. Army has shown that they can use a 1/4 ton trailer to transport fiber optic cables that replaced three 2 1/2 ton truckloads of CS-4566 conventional electrical cable.

2. Reasonable Maintenance

The multiplexing capability of optical fibers reduces the number and complexity of interfaces necessary. Combined with the simplicity of interfacing fiber bundles to the light source and detector without electrical or direct mechanical contact, the reliability of fiber optic systems is enhanced. Thus preventive maintenance, troubleshooting and repair costs are reduced. Also, because fiber optic cables are smaller and pound-for-pound stronger than electrical cables, they are less prone to damage.

E. ISOLATION

Isolation illustrates the use of the dielectric properties of optical fibers, namely, their inability to conduct

electrical currents. This attribute is important in situations where present technology requires additional components for preventing entry of unwanted electromagnetic energy. Such energy could be in the form of lightning, EMP, jamming, etc., all of which are generally precluded by devices in shunt or serial with each wire that otherwise would permit entry. The dielectric property alone of optical fibers means that such devices can be eliminated.

Optical fibers would provide complete isolation from receivers, there being no electrical ground required, which has the following advantages:

1. The receiver and transmitter do not require a common ground.

2. Repair of the fiber in the field can be accommodated even while the equipment is turned on.

3. Optical fibers could be used to traverse hazardous areas without fear of a short circuit or arcing which could cause ignition of volatile fumes or secondary explosions.

4. There are no effects due to ground currents in the proximity of the fiber.

F. NOISE IMMUNITY

Fiber optics conductors do not act as antennas that pick up and introduce into signal paths unwanted noise. Because of the high degree of noise immunity in fiber optics data links, the need for a variety of software and hardware error

detection and correction schemes required in noise susceptible systems are much less critical if not completely eliminated with fiber optic implementations.

G. HIGH TEMPERATURE AND VIBRATION TOLERANCE

Temperatures up to approximately 150°C can be tolerated by fiber optic cable. The cable can also withstand vibrations without experiencing electrical problems such as internal cable short circuits or changing electrical conducting characteristics.

H. REDUCED ELECTRICAL POWER REQUIREMENTS

Fiber optic light transmitting and receiving modules have the potential to require less electrical power to operate than an equivalent coax cable system.

I. SPECIFIC SHIPBOARD ADVANTAGES

As stated earlier, the weight and size of fiber optic cables are many times smaller for a given data transfer requirement than the corresponding metallic coaxial or twisted pair installation for the same requirement. The size and weight difference between metallic and fiber optic conductors leads to several distinct advantages, both economical and operational. Because of the ease in handling fiber optic conductors, installation difficulty, manpower costs and installation time can be minimized. Flexibility in installation is increased as it is possible to select alternative routing in fiber optic cable installation that

could not be considered in the case of metallic conductor coaxial cable or twisted pair because of their greater weight and bulk.

Multiplexing techniques are applicable to fiber optic data transmission systems. The extremely wide potential bandwidth of fiber optic conductors would allow many data channels to be realized using a single fiber in a frequency or time division multiplexing system.

Additionally, fiber optic multiplexing techniques could be applied to a wide variety of Navy data transfer systems now implemented with point-to-point metallic conductor signal paths. The fiber optic approach would eliminate tons of expensive metallic conductors from a typical Navy platform and substitute more easily installed and significantly less costly fiber optic conductors. Another advantage of the fiber optic multiplexing approach is that new systems may be more easily added to the platform since the need for point-to-point installation is eliminated by use of the multiplexing scheme. Added redundancy may be achieved in critical systems by use of parallel fiber optic multiplexing.

VI. PRESENT DISADVANTAGES

A. GENERAL

Two specific problem areas regarding military programs geared to fiber waveguides relate to strength of the fibers and their radiation resistance. The former is a universal problem concerning all users and manufacturers and has received worldwide attention. However, the latter is a military problem which basically must be solved by military research programs.

B. OPTICAL FIBER STRENGTH

Failure of glass under tensile stress results from the presence or introduction of flaws or microcracks on the surface. Stress at the crack tip, under tensile loading, increases many times over the value of the externally applied stress due to the leverage which is introduced by the long, thin crack geometry. The bonding strengths (approximately 3×10^6 psi) of the material are exceeded and the crack propagates inward, resulting in failure. Crack velocity in any given material varies with applied stress and environmental conditions such as temperature and relative humidity. Failure is further complicated by the chemistry at the crack tip, since the presence of water helps to reduce the strength of the silicate bonds resulting in sharply reduced strengths. All factors are equally important when

considering the development of high strength fibers. The main points are to achieve a flaw-free fiber surface, to maintain it by suitable coatings that provide mechanical protection and to exclude to the maximum extent possible, the presence of water or water vapor from the fiber surface. Another feasible approach is the surface compression strengthening of fibers. A compressive stress on the glass surface offsets applied tensile stresses which result in greatly reduced or eliminated crack tip stresses.

It is important to determine the present level of tensile strengths being obtained in commercial fiber laboratories. However, new techniques, such as Bell Labs furnace-drawn silica fibers coated with a UV-cured epoxy-acrylate, may have already solved the Navy's fiber strength problems.

C. RADIATION EFFECTS

Dielectric glass or plastic cables are particularly useful in nuclear environments due to their immunity to electromagnetic pulse (EMP) effects. However, many fiber optic cables suffer substantial losses in optical transmission when subjected to ionizing or nuclear radiation. The major problems which arise are associated with light-absorbing and light-emitting defect centers produced by the impinging radiation in the fiber waveguide itself. Substantial losses result in the presence of relatively low radiation levels due to the long optical path in most typical fiber optic systems.

The Navy was one of the first to recognize and measure the sensitivity of fiber optic materials to ionizing radiation. Damage mechanisms were identified and more emphasis was placed on developing more radiation resistant fiber materials. It was found that high purity fused silica is an extremely radiation resistant optical material. On the other hand, fused-silica-core, polymer-clad fiber material showed unacceptable radiation damage. It was also shown that the lead silicate type fibers on board the A-7 could not tolerate more than a few rads of irradiation without sustaining damage. Therefore, radiation hardening of all fiber optic data busses and cables is essential.

One problem in the application of fiber optics to military systems is that nuclear (and space) radiation is known to produce color centers in optical materials, causing a reduction of light transmission over a spectrum of wavelengths. Also, energetic radiation can generate light within optical materials. These and other radiation effects could cause permanent or temporary disruption of a fiber optics transmission system.

Samples representative of most of the optical fibers presently available in lengths of ten meters or more were tested for their responses to energetic radiation. Glass fibers doped with three levels of cerium were also prepared and tested. Permanent and transient x-radiation effect tests were performed using the Air Force Cambridge Research

Laboratories' (AFCRL) linear accelerator and flash x-ray machine [19]. Neutron effects tests were performed using the fast burst reactor at White Sands, New Mexico.

All of the fibers tested showed decreases in transmission when exposed to radiation. Commercial grade glass fibers were found to be the most radiation sensitive. They became virtually unusable in lengths greater than ten meters after exposure to only a few hundred rads of x-rays. Considering all of the tests performed, germanium doped fused silica fibers proved to be the least radiation sensitive of the fibers tested. Although plastic fibers' transmission decreased more rapidly with increasing x-ray dose, they showed more rapid recovery from both long-term and transient radiation effects than the germanium doped fused silica fibers. The radiation sensitivies of the cesium doped fibers were intermediate between the commercial grade glass and plastic fibers, with their radiation hardness increasing with increasing cesium doping.

All of the fibers emitted fluorescent light pulses when exposed to intense x-ray pulses. The fluorescent intensity emitted at the ends of the fibers, per unit length of irradiated fiber, was greatest for the commercial grade glass fibers and least for the fused silica fibers. The duration of the fluorescence following an x-ray pulse ranged from less than a microsecond for the plastic and fused silica fibers to several microseconds for the commercial grade and cesium doped glass fibers.

In summarizing these test results, germanium doped fused silica fibers appear to be the most radiation resistant of the fibers tested. The next most resistant to radiation damage are the plastic fibers, which have some advantages in faster recovery of transient induced transmission losses and lower neutron induced losses. The cerium doped glass fibers are more than an order of magnitude more resistant to radiation induced losses than the commercial glass fibers. The latter are very radiation sensitive and essentially unusable in radiation environments.

Radiation resistance is becoming a more important consideration in newer avionics programs. The plastic-clad fused silica bundle is presently being tested for use in military and commercial aircraft. Essentially plastic-clad fused silica bundles are attractive because of their high radiation resistance and systems redundancy. Future fiber optic shipboard and aircraft data links will tend toward redundant single-fiber channels, but presently, single-fiber sources and connectors are not practical or economical. Valtec's prices are presently in the $1.50 to $2.50 per meter range for a 10 dB/km graded index fiber in experimental quantities up to 50 Km.

D. SINGLE MODE FIBERS

Single mode optical fibers offer the optimum in overall propagation performance; however, exploitation of this performance has been limited by the difficulty in coupling

these fibers to other components and to other fibers. Their small cross-sectional dimensions (3-10 μm) require coupler alignment techniques with micrometer -level accuracies.

E. CONNECTOR COSTS

Since 1978, several connectors with less than 1 dB per interconnection have become available as have low loss splicing techniques. However, these connectors are still relatively unrealistically expensive. The proliferation of many different fiber sizes and cable configurations from the different manufacturers makes the realization of low cost, standardized connectors impractical at this time. Because the telecommunications industry will dominate the fiber market, standardization will only become a reality when these industries decide what is the most technically and economically sound approach for their implementation.

F. FIELD USAGE OF COMPONENTS

While fiber optics promise many advantages for data transmission systems utilizing this technology, there is really no substantial body of supporting field use data from which to accurately project what can be expected regarding reliability, survivability, maintainability and life cycle cost. However, these apparent discrepancies are only temporary in nature and will resolve themselves with continued use of fiber optic systems.

VII. SUMMARY

Substantial research and development investments by telecommunications, computer and military customers of fiber optics have led to the development of a new well-developed guided light technology. Efforts are presently under way to take components developed and tested in controlled environments and to incorporate them in full field demonstrations. These prototype systems demonstrations have the three-fold purpose of technically evaluating components and systems concepts, developing techniques for widespread field installation, and of demonstrating and establishing the practical performance advantages of fiber optics.

Optical fiber waveguide characteristics are now well enough known to accurately predict performance and to help in the design of optimized structures. Propagation loss in optical fibers has been reduced several orders of magnitude; a fact that has resulted in superior performance characteristics for fibers. Emphasis is now less on reducing the loss in fibers and more on the production of fibers with tighter tolerances and lower cost. Multi-mode graded index and step index, and single mode fibers have all been produced with low loss characteristics. Emphasis will be shifted to single mode technology when long distance moderate-to-high bandwidth (>100 Mbps) data links are

required. This will probably occur after substantial systems implementation of short length, low to moderate bandwidth economical links have been realized.

Cabling and coating of fibers are now receiving increased attention. Rapid advances are being made in reducing, both intrinsic fiber losses and stress optic losses, increasing fiber strengths and improving cable designs, so that none of these appear to be critical problems. While the optimum coatings and cabling designs have yet to be realized, significant and continuing progress has been realized, leading to several commercially available fiber cable prototypes.

Injection lasers and LED lifetimes have been improved by several orders of magnitude making sources with minimal acceptable performance available. Reliability of 10^5/hr is desired for most practical applications and extrapolated life-times in this range have been demonstrated. Activities in source development now include mode control studies, threshold reduction, modulation studies, heat sinking improvement, and packaging as well as reliability studies.

It appears that the age of optical communication has been born. The technical advantages are well documented and the capability for implementation is rapidly being acquired. A specialty market is all butensured by the unique properties and performance of dielectric optical waveguides.

The Navy's Shipboard Data Multiplex System and fleet signal transfer requirements were discussed and it was shown that the replacement of conventional wire with fiber

optics components is highly feasible in the near future. Electromagnetic compatibility and increased bandwidth alone are probably sufficient to warrant the replacement of wires by fibers in many of the SDMS systems, but many other advantages exist and clearly outweigh the major disadvantages.

An economic analysis was presented to review systems cost projections and compare optical fiber technology with the coaxial cable approach. It appears that the military capitalized the most on the early technology of fiber optics but they (the military) are slipping in status to a secondary position as the commercial world begins to dominate the fiber optics market.

VIII. RECOMMENDATIONS AND CONCLUSIONS

As discussed earlier in this thesis, there has been:

1. Widespread development of fiber optic components and systems within the past decade;

2. Several demonstrations as to specific avionic and shipboard applications have been made;

3. Demonstration of major performance gains in relation to coaxial or conventional systems, e.g.,

   a. high capacity - increased bandwidth,

   b. security - no compromising emanations,

   c. size and weight reduction - increases shipboard mobility (especially in submarines),

   d. dielectric isolation - no electrical currents, no short circuits, sparking or arcing,

   e. noise immunity - optics are EMI/RFI/EMP free,

   f. high temperature and vibration tolerance and,

   g. optics require reduced electrical power requirements.

4. Demonstration that fiber optics are economically feasible when given volume production considerations; and

5. Recommendations have been made by the NOSC on two separate occasions that future follow-on efforts be directed toward achieving operational shipboard fiber optic links.

It seems, from the preceding information, that widespread usage of fiber optic components and/or systems would be observed. However, this is not the case because currently, there is no operational ship using a fiber optics based system. In development and construction, there is only one major system, the Shipboard Data Multiplex System, and its designers do not include or plan to include, fiber optics implementation. Specifically, the system is in the engineering development model stage (EDM) under a 33 month contract which ends in 1981. This contract is one replacement of conventional cable with "less" conventional cable.

Since the SDMS contract, for example, does not include the use of fiber optics, one must ask, "Why not?" It is well known that in organizational behavior, there is usually a general resistance to change, but organizations do change. While this "implementation restraint" is a thesis topic in itself, it is useful to indicate some of its effects in the fiber optics case. Factors for not changing may include

1. Specifications not made or not clear enough;
2. Costs are too high;
3. Standardization of components has not yet been made;
4. Fiber optics have not been proven "beyond a doubt" that they work; and finally,
5. Ignorance on the part of the decision maker.

In all the above factors, the _risk_ involved in accepting a new technology is most important. Management has an attitude toward accepting risk and they will avoid projects viewed as too risky, i.e., a smaller but more certain net benefit is preferable to a possible large net benefit with a larger variance. When considering the risks involved, the two main issues between coaxial cable/conventional systems and fiber optics are the reliability and performance factors. For example, conventional wiring systems have been immensely reliable for long periods of time while fiber optic systems are just beginning to prove their reliability in use. On the other hand, when performance factors such as EMI/RFI/EMP, security, increased bandwidth (capacity), and weight are considered, fiber optics have proven their superior performance. It is true that conventional systems _may_ afford the same characteristics just described, but certainly not at a low technical and cost level. Therefore, if conventional systems are preferred over fiber optic systems, there is the implicit assumption that the reliability factor outweighs the performance factor.

Every decision maker has the prerogative to make any trade-off that seems desirable, but in the author's opinion, considering all the previously discussed factors, fiber optics implementation is the preferred choice. Specifically, the author is most concerned with the information processing capacity. Ships, in most cases, presently outlive their

internal system's information capacity, making it mandatory to realize that information requirements and capacity increases are inevitable.

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